MENTAL EFFORT

IN RELATION TO

GASEOUS EXCHANGE, HEART RATE, AND MECHANICS OF RESPIRATION

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INTRODUCTION

Of the factors known to influence metabolism profoundly, muscular work and the ingestion of food are among the foremost. Both these factors have had such marked effects upon the metabolism that they have been the source of a great deal of study. Hence exact information is now at hand regarding the effects of various degrees of muscular work, and we have a fairly comprehensive idea of the characteristic metabolic reactions to the ingestion of different kinds and quantities of food. Doubtless the sense of fatigue following intense, sustained mental effort, comparable in many instances to the subjective impressions of exhaustion following severe muscular exercise, has led to the conclusion that mental effort may justly be compared to muscular work. Thus the idea of work as such is incorporated in the titles and the discussions of many of the earlier papers bearing upon problems of mental effort, and not infrequently "mental work" and "muscular work" are compared in the same publication. An interesting correlation between mental effort and muscular work was noted by Loeb[1] in 1886 and some ten years later by Welch.[2] Basing his idea upon the well-known fact that it is practically impossible to carry out severe muscular work and mental effort at the same time, Loeb proposed to measure mental activity by the amount of muscular work that can be performed simultaneously. The idea has long been held that the mental process is of dynamic nature. An exhaustive treatment of this phase of the subject has been given by Lehmann.[3] Dodge,[4] basing his opinion upon the psychodynamics of Lehmann, clearly considers the mental process to be dynamic in nature. Both to the psychologist and to the physiologist studies of mental effort are important. Rubner[5] states,

"Die schwierigste Arbeit in der Naturerkenntnis ist vielleicht dem Biologen zugefallen, da er die Lebenserscheinungen im weitesten Sinne, also auch die Geistestätigkeit erforschen soll."

Indeed, the mental state has such a pronounced influence in many ways upon physiological reactions, particularly in pathological cases and in true psychosis, that *any information* regarding the effect of mental effort is of value.

The term "work" (or its equivalent in languages other than English) as applied to mental effort has the justification of long usage, since it has been freely employed by writers on this problem and invariably in a more or less definitely dynamic sense. Indeed, some[6] go so far as to compare the "psycho-ergogram" with the ordinary ergogram. The fact that the pulse rate usually increases during mental operations might at first lead to the conclusion that there is a dynamic factor in mental work. We have felt that the mental

[1] Loeb, A., Arch. f. d. ges. Physiol., 1886, **39**, p. 592.
[2] Welch, J. C., Amer. Journ. Physiol., 1898, **1**, p. 283.
[3] Lehmann, A., *Elemente der Psychodynamik*, Leipzig, 1905, p. 25.
[4] Dodge, R., Psychological Review, 1913, **20**, p. 1.
[5] Rubner, M., *Kraft und Stoff im Haushalte der Natur*, Leipzig, 1909, p. 9.
[6] S. de Sanctis, Riv. de Biol., 1924, **6**, p. 174.

process could be perhaps better expressed by the words "mental effort"[1] than "mental work," the former indicating sustained effort toward mental accomplishment without commitment as to whether there is any dynamic return or not. Hence in our considerations in the following pages we shall avoid the use of the expression "mental work." Since our findings in large part controvert the idea that the mental process has a significant dynamic effect, the phraseology "mental effort" seems to be more consistent. Critics, however, may take the ground that this is a mere quibbling over terms and that the situation has not really been bettered. Avoidance of the term "work" is, we believe, justifiable. Substitution of the term "effort" may not give an ideal expression but at least has the advantage of avoiding the positive term "work."

[1] In an article brought to our attention unfortunately only after this manuscript had gone to press, we find the dynamic factor definitely expressed by G. H. Rounds, H. J. P. Schubert, and A. T. Poffenberger (Journ. Gen. Psychol., 1932, **7**, p. 67) who state that they "accept as a starting point the view that mental work uses energy."

EARLIER INVESTIGATIONS ON THE EFFECTS OF MENTAL EFFORT UPON METABOLISM

Examination of the literature indicates that there are two general methods of studying the problem of the influence of mental effort upon metabolism: (1) that which we chose for our research, namely, the measurement of the *total* metabolism during intellectual activity, and (2) the measurement of some localized factor. In accordance with the localized method, observations have been made of the temperature of the head and the brain during mental activity, the morphology and metabolism of the brain, the chemistry of the blood going to and from the brain, and the concomitant vasomotor changes in the skin of the body and the blood temperature. These localized studies have been carried out for the most part chiefly with animals. Efforts to study the local metabolic factors in the brain are carried out with humans only with difficulty, and those experiments made on the lower animals dealing, for example, with the blood supply and with the gaseous exchange of the brain (by analysis of the blood going to and from the brain) can be of little interest in our particular problem in which sustained severe mental effort (presumably possible only in the case of intellectual humans) is being considered.

As a result of the concept that mental and neural activity result in a more rapid disintegration of brain and of nerve tissues which are rich in phosphorus, the reported increase in the excretion of phosphorus in the urine during mental effort has received not a little experimental attention. Another method of attack has been to study the heart rate during mental activity, on the general theory that since an increase in heart rate *a priori* means an increase in metabolism, an increase in heart rate accompanying mental effort must therefore signify an increase in metabolism. The most important line of study, however, has been the persistent attempt with continually refined technique to note the effect, if any, of mental effort upon the entire metabolic process. Thus measurements have frequently been made of the carbon-dioxide elimination and occasionally of the oxygen consumption of the entire body prior to and during mental effort.

Of these more or less distinct lines of investigation our own research has to deal only with the last two mentioned above, for our studies are concerned exclusively with the energy exchange, the mechanics of respiration, and the circulation, and we have not been particularly interested in the more subtle chemical studies of blood and urine or the localized studies of the brain. Nevertheless we deem it advisable to discuss in a general way some of the important features of the earlier localized studies and the earlier studies on the respiratory metabolism during mental effort before passing to a consideration of our own experimental results, inasmuch as a digest of the literature on these fundamental earlier experiments is necessary to a complete understanding of our problem.

CEREBRAL, URINARY, AND CIRCULATORY STUDIES

Cerebral thermometry—As a result of the concepts of a greatly increased blood flow to the head and of a theoretically probable increase in localized

temperature, the earliest comprehensive studies of mental activity in its relation to metabolism and dynamics were carried out by thermometry. Peculiar interest attaches to the fact that Lombard[1] in Boston published, in 1879, the first observations of this nature on humans. An extensive study of the temperature of the brain was reported by Mosso[2] in 1894, who compared the brain temperature with temperatures in other parts of the body. Unfortunately the thermo-junction was not in general use at that time, and Mosso employed the sluggish, less sensitive mercury thermometer. The earlier attempts to study the localized effects of mental activity, dealing with temperature measurements on the surface of the brain, in the brain cavity, or on the skin of the head, have been admirably summarized by Pembrey[3] in his treatise on animal heat. In the classic monograph of Gley[4] the whole problem is likewise well discussed, with a consideration of the status of the researches in this field up to 1903. Three years later Fleury[5] presented at the 1er Congrès International d'Hygiène Alimentaire a review of the researches in cerebral thermometry, with special reference to the work of Mosso and of Leonard Hill and Nabarro.

Morphology and metabolism of the brain—In a recent contribution on the brain with special relation to weight and form, Donaldson,[6] in a keen analysis, has brought out the significant fact that most of the considerations of the form and weight of brains, both of scholars and of hospital whites and negroes, have led to no conclusive results to explain the superior intellect of the scholars. On the other hand, Donaldson emphasizes the studies of Hindzé[7] on the vascular tree in the pia, stating that Hindzé has noted a positive correlation between the complexity of the vascular tree and the mental grade. Here, as Donaldson points out, "is something measurable and of fundamental importance."

Cobb,[8] recently reporting on the cerebral circulation on the basis of his own findings and the studies of Wearn,[9] Krogh,[10] and Craigie,[11] states that "cardiac muscle has approximately 11,000 mm. of capillary length per cubic millimeter of tissue; active skeletal muscle has 6000, but at rest only 2000; the grey matter of the brain varies from about 500 to 1000 mm. of capillary length per cubic millimeter, and the white matter may run as low as 200." Thus it appears that the brain can not be a seat of active combustion, since the length of the capillaries in the brain per cubic millimeter of tissue is the least of all the tissues. On the other hand, from the standpoint of hydrodynamics the brain is especially well adjusted for extensive circulation.

[1] Lombard, J. S., *Experimental researches on the regional temperature of the head, under conditions of rest, intellectual activity, and emotion*, London, 1879.

[2] Mosso, A., *Die Temperatur des Gehirns*, Leipzig, 1894.

[3] Pembrey, M. S., Schäfer's *Text-Book of Physiology*, London, 1898, **1**, p. 807.

[4] Gley, E., *Études de Psychologie Physiologique et Pathologique*, Paris, 1903.

[5] Fleury, M. de., Revue Soc. Sci. d'Hygiène Alimen., 1906, **3**, p. 855.

[6] Donaldson, H. H., Amer. Journ. Psych., 1932, 12, p. 197.

[7] Hindzé, B., *Les artéres du cerveau des hommes d'élite.* Bull. et Mém. de la Société d'Anthropologie de Paris, Séance du 2 décembre, 1926; *ibid., Wie sollen wir die Hirnarterien verarbeiten? Zur Methodik der makroskopischen Erforschung der Hirnarterien.* Institut der normalen Anatomie der I. Moskauer Staatsuniversität, 1930.

[8] Cobb, S., Annals of Internal Medicine, 1933, **8**, p. 292; Cobb, S., and J. H. Talbot, Trans. Assoc. Amer. Phys., 1927, **42**, p. 255.

[9] Wearn, J. T., Journ. Clin. Investig., 1924–25, **1**, p. 572.

[10] Krogh, A., *The anatomy and physiology of capillaries*, Yale Univ. Press, 1924.

[11] Craigie, E. H., Journ. Comp. Neurol., 1920, **31**, p. 429, and 1921, **33**, p. 193.

Thus, as Cobb says, "it has been shown[1] that there is a rapid flow of blood in the brain of anæsthetized animals, the speed being as great as, or greater than, that in any other organ of the body with the possible exception of the retina, which is indeed part of the brain."

As already stated, it is our belief that whatever contributions may be made to the general physiology of the brain by observations upon the lower animals, such observations can have little, if any, bearing upon the specific problem of the effect of sustained mental effort upon the metabolism of humans. Mental effort, in our judgment, is possible only with intellectual human beings. Nevertheless the observations of Alexander and Cserna and especially the comments thereon of Liebermann are worthy of note. Alexander and Cserna[2] have found that the metabolism of the brain of the dog may be from 60 to 90 per cent lower under narcotics than in the normal waking condition, and Loewy[3] has concluded that the metabolism does not decrease during normal sleep.[4] Based upon these observations, Liebermann[5] makes the suggestion that the total effect of mental activity remains constant all the time, that during severe mental activity there is a concentration of the effect, whereas under normal conditions, even in sound sleep, the effect is diffused.

Holmes[6] has given an excellent review of the metabolism of brain and nerve. He states that "our information about the oxidative processes of the brain is, for obvious technical reasons, far less complete than about those of nerve. The large oxygen consumption of grey matter makes it difficult to ensure that isolated portions of brain are properly supplied with oxygen under experimental conditions. There is at present no method by which it can be shown that isolated brain cells are in a state of activity. On the other hand, operative procedures, by which the metabolism of the organ *in situ* might be determined, are hampered by the fact that they necessarily entail anæsthesia, which at once frustrates the purpose of the experiment." Our examination of the studies made with the Warburg apparatus on the oxidative capacity of brain tissue leads us to believe that, although such studies contribute information regarding the rôle played in metabolism by isolated, quiescent brain tissue, they throw no light upon the metabolic effect of activated brain tissue *in situ* during extreme mental activity.[7]

In studying the effect of mental effort on cerebral circulation Lennox,[8] in fifteen instances of patients with epilepsy, drew blood from an internal jugular vein before and during the reading and performance of problems in mental arithmetic. In two-thirds of these instances there was an increase in the oxygen content and a decrease in the carbon-dioxide content of the blood leaving the brain. The average increase in the oxygen content for the fifteen cases was 0.9 per cent by volume, an amount well outside the limits of average normal variation. Lennox concludes that the observed increases are presumably ascribable to a dilatation of cerebral vessels. The respiratory

[1] Wolff, H. G., and H. Blumgart, Arch. Neurol. and Psych., 1929, **21**, p. 795.
[2] Alexander, F. G., and S. Cserna, Biochem. Zeitschr., 1913, **53**, p. 100.
[3] Loewy, A., Berl. klin. Wochenschr., 1891, **28**, p. 434.
[4] Unpublished Nutrition Laboratory findings are contrary to this view.
[5] Liebermann, L. v., Biochem. Zeitschr., 1926, **173**, p. 181.
[6] Holmes, E. G., Annual Review of Biochemistry, Stanford University, 1932, **1**, p. 497.
[7] Much this same opinion has also been expressed by E. Grafe, Bethe's Handb. d. normalen u. pathologischen Physiologie, 1928, **5**, p. 201.
[8] Lennox, W. G., Arch. Neurol. and Psych., 1931, **26**, p. 725.

quotient, which is admittedly only a qualitative index of metabolism, is according to Lennox relatively high in the brain, and he found more dextrose disappearing from the blood in its passage through the brain than in its passage through the extremities.

Chemistry and morphology of blood and urine—Kestner and Knipping,[1] acting upon the suggestion of Embden,[2] studied the phosphoric acid in the plasma of some of their subjects and noted a pronounced increase during mental activity. This increase they interpreted as being of special significance in disturbing the acid-base relationship and liberating carbon dioxide, thus affecting the respiratory quotient. Suk[3] compared blood sugar determinations obtained with a group of students who had devoted three months to physical training with some determinations secured with two other groups of students who had spent the same period of time in intensive studying. From observations made before and after the periods of physical and mental activity, he found that the two groups of students who engaged in strenuous and continual mental effort for three months showed a marked decrease in the sugar content of the blood. Suk is convinced that mental effort affects the whole metabolism of the body and, indeed, to a considerable extent. The difficulties of studying this subtle question of the chemistry and morphology of the blood are nowhere more clearly shown than by the recent communication of Dunajewski and Kaplan,[4] who found that the original reports of Goldberg and Lepskaja[5] in 1927 can not be confirmed and who believe there is no change in the blood picture as a result of mental effort.

The finding of especially phosphorus-rich compounds in the brain tissue led to the early belief that mental effort affects profoundly the disintegration of such compounds and results in an increased excretion of phosphorus in the urine. The popular expression of Moleschott "Ohne Phosphor kein Gedanke" undoubtedly stimulated the research in this direction. Again it is to French writers that we turn for complete statements regarding the history of this feature of the study of mental effort. Thus, Fleury[6] writes:

> "Mosler, et après lui Donders avaient cru constater que le travail intellectuel intense augmentait le contenu total de l'acide phosphorique dans l'urine. Byasson, dans une thèse partout citée, conclut aussi à une élimination plus grande de l'acide phosphorique et de l'urée."

Lescoeur,[7] in 1911, summarized the divergent findings in the literature prior to that date regarding the relations between certain urinary coefficients and different types of human activity, especially intellectual activity. Taranowitsch,[8] in 1928, maintained that prolonged mental fatigue increased the organic phosphorus content of the urine. Since this time we have been unable to find any positive contribution to this subject.

[1] Kestner, O., and H. W. Knipping, Klin. Wochenschr., 1922, 1. Jahrg., No. 27, p. 1353; Knipping, H. W., Zeitschr. f. Biol., 1923, 77, p. 165.

[2] Embden, G., and E. Adler, Zeitschr. f. physiol. Chem., 1922, **118**, p. 1; Lange, H., and M. Simon, Zeitschr. f. physiol. Chem., 1922, **120**, p. 1.

[3] Suk, V., Bull. Internat. Acad. Sci. Bohême, 1925.

[4] Dunajewski, M. J., and P. M. Kaplan, Arbeitsphysiologie, 1933, **6**, p. 437.

[5] Goldberg, A. Ph., and M. W. Lepskaja, Zeitschr. f. d. ges. exp. Med., 1927, **56**, p. 181.

[6] Fleury, M. de, *loc. cit.*

[7] Lescoeur, J. A. L., *Sur les relations qui existent entre certains coefficients urinaires et les divers modes de l'activité humaine, principalement le travail intellectuel,* Lille, 1911.

[8] Taranowitsch, L. E., Biochem. Zeitschr., 1928, **194**, p. 461.

To the psychiatrist the effects of mental effort, particularly intense mental excitation, are naturally of great interest. Hence any phase of the study of the effects of mental effort must be considered as contributory to our general knowledge of the complex metabolism of the brain. It is impossible to differentiate between the various phases of mental or neural excitation in much of the earlier research, but among the numerous analyses of the urine in studies concerned with the effects of mental effort, determinations have been made of the urinary nitrogen output accompanying intense nervous excitement. Thus comparisons of the nitrogen excretion in the 24-hour urine during relative mental repose and during great nervous excitement have shown that the nitrogen metabolism underwent no noticeable change during the period of nervous excitement.[1]

Pulse rate and blood pressure as indices of mental effort—In 1909 Benedict and Carpenter[2] published the results of experiments on the influence of muscular and "mental work" on metabolism, which included observations on the pulse rate. Dodge,[3] in 1913, reported the results of a study of the effects of "mental work" considered from the standpoint of psychodynamics. His observations were based upon the supposed correlation between pulse rate and metabolism and were confined to exact measurements of pulse rate in relatively short periods. Dodge pointed out that the Nutrition Laboratory had noted that an increase in pulse rate is frequently accompanied by an increase in metabolism. He stated that "The relatively small energy transformations of mental work is not a surprise," and yet he considered the pulse rate as proof of the existence of a real increase in metabolism. In so far as experimental evidence was available at the time of Dodge's paper, this generalization regarding the correlation between pulse rate and metabolism was true and perhaps Dodge was fully justified in assuming that if an increase in pulse rate accompanies mental effort, there must necessarily be an increase in metabolism. However, since the publication of Dodge's paper, the Nutrition Laboratory has accumulated data demonstrating that this generalization is by no means true in all cases. Thus Smith[4] has found that a man standing quietly may have a heart rate actually higher than the same man when walking at a moderate pace, even though his metabolism is increased 100 to 200 per cent by the effort of walking. Other instances of irregularity in the relationship between pulse rate and metabolism have been noted, at least sufficient to rule out the use of the pulse rate as a measure of the metabolism, particularly as a measure of the minor changes in metabolism noted during mental activity. In a study of the vascular processes, Day[5] found with both adults and children an increase in pulse rate during mental exercise and a decrease following the completion of the mental exercise. The fluctuations in systolic and diastolic blood pressure were not concomitant with the changes in pulse rate. There was no observable regularity in the increasing and decreasing pressure, and Day concludes that, unlike the pulse rate, the blood pressure was not significantly affected by the mental exercise given in her investigation. Gillespie[6] found increases in both the pulse rate and the

[1] Benedict, F. G., Amer. Journ. Physiol., 1902, **6**, p. 398.
[2] Benedict, F. G., and T. M. Carpenter, U. S. Dept. Agric., Office Expt. Sta., Bull. 208, 1909.
[3] Dodge, R., *loc. cit.*
[4] Smith, H. M., Carnegie Inst. Wash. Pub. No. 309, 1922, pp. 165 and 310.
[5] Day, M. E., Journ. Comp. Psychol., 1923, **3**, p. 333.
[6] Gillespie, R. D., Journ. Physiol., 1924, **58**, p. 425.

blood pressure during mental activity. These increases were independent of emotional factors and were not accounted for by movements of the articulatory muscles or by known muscle tensions. With 13 university students, Tigerstedt[1] noted the systolic pressure before and after a 6-hour written examination and also during a control period. These observations, although not made during mental effort, were secured when the students were clearly under nervous excitement not far removed from mental effort. Tigerstedt ascribes the striking increase found in the blood pressure prior to the examination to the effect of a psychical reflex partly upon the blood-vessels and partly upon the adrenals. His observations therefore show another dynamic effect, undoubtedly secondary in nature, resulting probably from a combination of mental activity and psychical disturbance.

GASEOUS METABOLISM STUDIES

A number of writers, notably Grafe,[2] have made admirable collections of the literature concerning the influence of mental effort upon the gaseous exchange. Lavoisier,[3] in discussing his fundamental respiration experiments with Seguin, considers the potentialities of this type of physiological study and points out the importance of investigating the energy relations involved in mental effort. However, no experiments exactly of this nature were reported by him. Liebermeister[4] comments that a single experiment (he gives no details regarding his technique) gave a result for carbon-dioxide production that seemed to support, although not conclusively, the assumption that mental activity increases heat production. One of the first attempts to study definitely the effect of intellectual activity upon the gaseous metabolism was made by Speck,[5] who considered the relationship between mental effort, respiration, and metabolism and reviewed the literature on the subject. Although he found with some uniformity a small increase in metabolism during mental effort, he concluded that mental activity has no direct influence on metabolism and that the mental process does not involve oxidation or cleavage processes or at least that they are so small that by the methods then existing they could not be measured. The increase in metabolism (10 per cent) he was inclined to attribute to muscular movements, due in general to the discomfort of the body position maintained during the experiments.

The relationship between mental activity and mental repose has been intimately associated with the problem of the metabolism of an individual while asleep and while awake. Loewy,[6] studying the effect of hypnotics, found no change in the metabolism during natural sleep (contrary to the experience in the Nutrition Laboratory), and but a slight diminution during sleep following the giving of morphine. Johansson[7] has commented briefly

[1] Tigerstedt, C., Skand. Arch. f. Physiol., 1926, **48**, p. 138.

[2] Grafe, E., *Die pathologische Physiologie des Gesamtstoff- und Kraftwechsels bei der Ernährung des Menschen*, Munich, 1923, pp. 411–426; *ibid.*, Bethe's Handb. d. normalen u. pathologischen Physiologie, 1928, **5**, pp. 199–211.

[3] Seguin and Lavoisier, Mémoires de l'Academie des Sciences, 1789, p. 185; *ibid.*, Oeuvres de Lavoisier, Paris, 1862, 2, p. 697.

[4] Liebermeister, C., Handb. d. Pathologie u. Therapie des Fiebers, Leipzig, 1875, p. 196.

[5] Speck, C., Arch. f. exp. Pathol. u. Pharmakol., 1881, **15**, p. 81; *ibid.*, *Physiologie des menschlichen Athmens*, Leipzig, 1892, pp. 189–209.

[6] Loewy, A., *loc. cit.*

[7] Johansson, J. E., Skand. Arch. f. Physiol., 1898, **8**, p. 103.

upon the effect of mental activity and the associated alterations in the mechanics of respiration upon the carbon-dioxide production.

The experiments in the respiration calorimeter at Wesleyan University, Middletown, Connecticut, reported in 1897 by Atwater, Woods, and Benedict,[1] included one in which the subject studied a German treatise. The experiment was by no means ideally designed and is therefore chiefly of historic interest. As a natural consequence of this experiment, a comprehensive study of metabolism during mental effort was carried out with the same apparatus somewhat over a decade later by Benedict and Carpenter.[2] Since these observations of Benedict and Carpenter have aroused considerable discussion and since they are the basis for much of our present research, an analysis of them here is justified. Experiments were made with twenty-two college students individually, each participating in a 3-hour written examination inside the respiration chamber, during which time measurements were made of the carbon-dioxide elimination, the oxygen consumption, the water-vapor output, and the heat production. Control measurements were carried out somewhat later, after a meal of approximately, although by no means exactly, the same composition as before and at as nearly the same time after food as in the examination period. During an examination week in a university it is impossible to secure students for control periods, as they are all occupied with examinations. Since the experiments included 22 men, nearly a month had to elapse before a control day with each one could be secured. These control experiments have been criticized on the ground that there is a seasonal variation in metabolism and that the slight differences in metabolism noted by the authors between the control experiments and the mental effort experiments may be accounted for wholly by a seasonal variation in metabolism. At the time this criticism was raised, little was known with regard to the influence of season on metabolism. Only recently has it been shown that the metabolism undergoes a slight seasonal variation,[3] which, however, during the period when these experiments were carried out (February and March) would be wholly insignificant. Hence, although theoretically this criticism is plausible, practically we consider it without value.

The greatest defect in the observations of Benedict and Carpenter was, we believe, not the time elapsing between the examination and the control periods, but the fact that they were studying the effect of a factor of a very small order of magnitude and that factor superimposed on a baseline that did not represent the irreducible minimum or basal metabolism. Calculations made subsequent to the published report of these observations have shown that, under the conditions of experimenting, the metabolism of these students while inside the respiration chamber, both during the mental effort and the control periods, was on the average 46 per cent above their probable basal metabolism according to modern prediction tables.[4] The students were measured after food, were sitting and engaged in a small amount of

[1] Atwater, W. O., Woods, C. D., and F. G. Benedict, U. S. Dept. Agric., Office Expt. Sta., Bull. 44, 1897, p. 51.

[2] Benedict, F. G., and T. M. Carpenter, U. S. Dept. Agric., Office Expt. Sta., Bull. 208, 1909; see, also, Benedict, F. G., Proc. Amer. Philos. Soc., 1910, 49, p. 145.

[3] Gustafson, F. L., and F. G. Benedict, Amer. Journ. Physiol., 1928, 86, p. 43.

[4] Harris, J. A., and F. G. Benedict, Carnegie Inst. Wash. Pub. No. 279, 1919, tables I–IV, pp. 253–266.

activity during the experiments, including the control periods. Hence the effect of mental effort was superimposed upon a high initial baseline, and the slight increment in metabolism actually noted was smaller, percentage-wise, than it would have been if referred to a lower baseline. Furthermore, under the conditions prevailing during the control periods, the baseline might be 45 per cent above the true basal value on one day, 50 per cent above on another day, and 55 per cent above on still another day. The differences in these levels would entirely obscure any effect, if it existed, of mental effort. In the experiments that we shall report in the following pages this defective procedure was avoided.

The pulse rates recorded during these experiments of Benedict and Carpenter have been seriously criticized by Dodge.[1] It is obvious that pulse rates taken at the wrist by an untrained subject himself can have only a general interest. At the time these experiments were made, in 1905, or twenty-eight years ago, suitable technique for the objective recording of the heart rate was not available. Dodge has given altogether undue prominence to his treatment of these pulse rate records. It is significant that the pulse rate was *only one of five factors* considered by Benedict and Carpenter in their studies and that their deductions were by no means based upon this one factor. Yet we agree with all of Dodge's criticisms as to the imperfections in these records of pulse rates. Benedict and Carpenter, in summarizing their results, conclude:

"On the whole, however, the increase of both of these factors (carbon-dioxide elimination and heat production) accompanying the mental exertion is so small and the exceptions are so numerous that it would not be wise to say whether or not the mental activity exercised a positive influence on metabolic processes in general."

At the end of their article, however, is the following positive statement:

"We are very strongly of the opinion that the results obtained in these experiments do not indicate that mental effort has a positive influence on metabolic activity."

In making his review of the literature, Grafe[2] unfortunately selected the first of these statements, which admittedly is poorly expressed.

On January 12, 1913, Carpenter and Dodge at the Nutrition Laboratory made a single experiment (unpublished) with a medical student upon the effect of short periods of mental activity (multiplication) upon the oxygen consumption. The oxygen absorption was measured graphically from the record of the movements of the spirometer of the universal respiration apparatus. One period of 2.9 minutes and two periods of 6.9 and 6.1 minutes of multiplication resulted in an increase of 12 per cent in the oxygen absorption over the normal absorption measured immediately preceding the periods of multiplication. Reading to the subject produced no change in metabolism. This increase of 12 per cent may have been due to an initial increase in metabolism which may take place at the beginning of mental effort, or it is possible that the periods were too short to measure such changes in metabolism

[1] Dodge, R., *loc. cit.*

[2] Grafe, E., *Die pathologische Physiologie des Gesamtstoff- und Kraftwechsels bei der Ernährung des Menschen*, Munich, 1923, p. 421.

accurately. The experiment was only preliminary, but at least indicates the possibilities of this method of attack.

From unpublished experiments on the oxygen consumption of students during mental effort, Amar[1] concludes that intellectual activity does not result in a measurable expenditure of energy.

Lehmann in Copenhagen, with his associates, Becker and Olsen,[2] based their study of the effect of mental effort entirely upon measurements of the carbon-dioxide elimination. Their criticism of the results of Benedict and Carpenter, particularly regarding the control periods and the possible existence of seasonal variations in metabolism (see page 13), have been given serious consideration by all writers since the publication of their report. Against the theoretical side of their criticism we have no argument, but practically, in view of the small effect of season upon metabolism, we believe their criticism is without significance. The paper of Becker and Olsen has for a long time been unchallenged save by Lehmann himself, who unfortunately questioned it in a Danish publication[3] which was wholly inaccessible to us at the time we were making our experiments. The Nutrition Laboratory, in common with many other laboratories, thought when this article first appeared that it was sponsored by that master physiologist, Professor August Krogh, and, in addition, that advice had been secured from the two eminent Danish scientists, Professors Møllgaard and Fridericia. It therefore seemed as if technically the investigation could hardly be criticized. After a number of years, however, in going over the paper carefully, we found such astonishing inconsistencies in it that we specifically asked Professor Krogh to what extent he had supported this research. We are permitted by him to quote that he was in no wise responsible for it, that he criticized it at the time in many ways, and that he felt especially that it was unsound to base the measurements on carbon-dioxide exhalation. Through a personal communication from Professor Krogh we learn that Professor Lehmann himself, in 1918, before the Danish Academy (K. D. Videnskabernes Selskab) retracted the former results and admitted that he could find evidence only of variations in muscular tension during mental effort. Under the circumstances it hardly seems necessary to criticize the paper of Becker and Olsen, although it has received a great deal of attention from various writers.

It is most unfortunate that the retraction of Professor Lehmann has remained so long undiscovered in this Danish publication. Since the article is in Danish, it is impossible for us to make a suitable digest of it. Furthermore, the English resumé of a little over two pages given at the end of the article is not easily interpretable without many of the details. This Danish paper of Lehmann, if we have interpreted it correctly and we recognize the difficulty of so doing, seems to be a striking illustration of the difficulty of studying with ordinary (1917) metabolism technique such a subtle factor as the effect of mental effort, which must be superimposed upon the basal metabolism. Presumably his subjects, three in number, were without food for 12 hours, inasmuch as only two experiments (L-19 and L-20) were specifically

[1] Amar, J., *Le moteur humain*, Paris, 1914, p. 279.

[2] Becker, F. C., and O. Olsen, Skand. Arch. f. Physiol., 1914, **31**, p. 81; Lehmann, A., Bericht ü. d. V. Kongress f. exp. Psychol. in Berlin, 1912, p. 136.

[3] Lehmann, A. K., Danske Videnskabernes Selskabs Skrifter, Natur. og. Math. Afdeling, 1918, **3**, (ser. 8), No. 2, p. 211.

stated to be three hours and one hour, respectively, after food. The experimental program lasted in general not far from an hour or an hour and 10 minutes, occasionally 1 1/2 hours. Unfortunately the subjects had only one preliminary 10-minute rest period prior to the mental effort. There were two rest periods after the mental effort, but the entire effect of the mental effort was referred to the first 10-minute period as a baseline. The danger of using a single 10-minute period in this way is obvious. *If* these experiments were made with the subjects in the post-absorptive state, under the same conditions of physical rest, then one should be able to compare directly the oxygen consumption per minute from day to day. Lehmann has employed the unusual method of expressing the oxygen consumption in cubic centimeters per second, but we have recomputed his results on the basis of the consumption per minute. There is a striking difference with all three subjects between the rest value before and the average of the two rest values after the mental effort period. With subject L the maximum consumption of oxygen in the preliminary rest period was 214 c.c. and the minimum 131 c.c. per minute. In the rest periods after the mental activity this subject had a maximum consumption of 198 c.c. and a minimum of 98 c.c. Thus the extreme variation during rest was from 98 to 214 c.c. This variation in the resting basal or "standard" metabolism is never experienced in normal metabolism measurements, especially with well-trained subjects like those of Lehmann. With his second subject, N, the oxygen values in the single periods prior to the mental tests range from 323 to 259 c.c. per minute and in the rest periods after mental effort from 298 to 254 c.c. The variation here is from 254 to 323 c.c. With his third subject, P, the values in the single periods before the mental tests range from 263 to 140 c.c. and in the periods after mental effort from 258 to 116 c.c. The extreme range is from 116 to 263 c.c.

Exact uniformity in the standard metabolism from day to day is by no means to be expected. Such variations as these, however, even if the subject is not post-absorptive, are outside the experience of the Nutrition Laboratory (see further discussion of this point on page 68), and we believe that individuals showing such a variable metabolism are not suitable subjects with whom to study the possibly subtle effects of mental effort. It is true that Lehmann does not compare the metabolism from day to day but compares the basal value on each day with the subsequent values obtained on that same day during mental effort. However, the tremendous decrease in metabolism noted between the initial period before and the two periods following the mental effort is again outside the experience of the Nutrition Laboratory and leads us to believe that the value for the initial period is usually too high. On this ground, therefore, one is justified in concluding that the *increases* supposedly obtained by Lehmann are in reality *too small*. The variability noted by him in the respiratory quotients found on any experimental morning was also so great as to be outside our experience. In view of these figures we feel that Lehmann was particularly unfortunate in his technicians. Therefore, although on the basis of this second research he has retracted (according to Professor Krogh) the findings of his two students, Becker and Olsen, one doubts on a critical examination of his published protocols whether such retraction is justified solely on the basis of the experimental findings.

Although much criticism has been leveled at the procedure of Waller and De Decker[1] in measuring the carbon-dioxide exhalation only, when studying the caloric needs of laborers, one of their findings has bearing upon this problem of intellectual activity. Examining proof-readers in a printing office, they found no increase in metabolism above basal during the mental effort of proof-reading.

In 1922 Kestner and Knipping[2] reported the results of a study with the universal respiration apparatus of the Nutrition Laboratory, in which the gaseous exchange of seven subjects was measured before and during mental effort. With several subjects they also determined the excretion of phosphorus in the plasma (see page 10). The mental effort consisted for the most part of reading from a complicated treatise. In some instances arithmetic problems were solved. The respiratory quotients almost invariably were lower during the mental effort, some of them much lower than would be expected. Thus at least three in the series were 0.7 or below. The increases in oxygen consumption during the mental effort were considerable, varying from 3 to 23 per cent. Even if this latter value of 23 per cent and the results of the experiment with a child are omitted, because the respiratory quotients are certainly questionable and the oxygen values seem extraordinarily high, the increases range from 3 to 22 per cent. They consider that the average increment of 7 or 8 calories per hour above the basal energy requirements is so small in relation to the total daily needs that it is insignificant. They are inclined to lay more stress on the considerable increases of phosphorus in the blood. They conclude that there is no marked increase in the energy expended as a result of mental effort, but, as Grafe has pointed out,[3] it is difficult to understand how they can make this deduction in view of the great increases in oxygen consumption noted in some of their experiments.

The error of studying the effect of mental effort by measuring the carbon-dioxide elimination only, as was done by Becker and Olsen, is clearly brought out by Kestner and Knipping. With one of their subjects they measured the carbon-dioxide excretion during repose and then at the beginning and at the end of mental activity. During the rest period it was 167 c.c. per minute, at the beginning of mental effort 197 c.c. and at the end 172 c.c. The respiratory quotients were 0.91, 0.93 and 0.80, respectively. These results indicate the tremendous lability in the carbon-dioxide elimination.

Perhaps one of the most important studies of this subtle problem is that carried out by Ilzhöfer[4] in the laboratory of the late Professor M. von Gruber in Munich. Ilzhöfer, using the Krogh apparatus, made observations on six subjects. His research was most carefully planned, but unfortunately did not include determinations of the respiratory quotient and the pulse rate during the intellectual activity. The increments in ventilation of the lungs during the period of mental effort were in many cases very large. The respiration rate per minute was greatly increased, but the depth of each respiration was usually decreased. Ilzhöfer calculates the energy expenditure from the

[1] Waller, A. D., and G. De Decker, British Med. Journ., 1921, 1, p. 669.

[2] Kestner, O., and H. W. Knipping, Klin. Wochenschr., 1922, 1. Jahrg., No. 27, p. 1353; Knipping, H. W., Zeitschr. f. Biol., 1923, 77, p. 165.

[3] Grafe, E., *Die pathologische Physiologie des Gesamtstoff- und Kraftwechsels bei der Ernährung des Menschen*, Munich, 1923, p. 424.

[4] Ilzhöfer, H., Arch. f. Hygiene, 1924, 94, p. 317.

measured oxygen consumption and concludes that on the whole there is a small increase in metabolism, seemingly proportional to the intensity of the mental effort. This increase varied, on the average, from 1 per cent with light mental activity to from 2.3 to 8.6 per cent with intense mental effort. Part of this increase, but only a small part, Ilzhöfer ascribes to the mechanics of respiration. There remains even then an increase on the average of 0.6 per cent during light mental effort and 3 per cent with intense mental effort. No increase in the heart rate was noted, and hence no allowance was made for that. The importance of selecting the type of mental effort that is suitable to the individual is emphasized. Most of the observations dealt with the effect of reading. Only one of his subjects used mathematical calculations as the source of intense mental effort. We are inclined to think that his method of securing sustained, intense mental effort was not so good as that of the Russian investigators. Nevertheless he succeeded in obtaining what was, objectively at least, intense mental activity and, as Grafe[1] has properly said, his investigation represents a most accurate study of this subject.

The mechanics of speech or voice control enters so instinctively into the use of audible speech that a study of the metabolism during speaking, either with restrained muscular activity[2] or with the muscular freedom of the lecturer, is hardly suited to throw light upon the more subtle problem of the effect of mental effort *per se* upon metabolism. Schroetter[3] made observations on the respiratory exchange of a professional speaker, and R. Tigerstedt[4] determined the energy expended during a lecture. The Nutrition Laboratory studied college students while reading aloud and found no significant increase in metabolism.[5] But since these determinations were made upon subjects under conditions necessitating a not inconsiderable amount of extraneous muscular activity, they are only of indirect interest here. Chlopin especially considered the factor of extraneous activity and believed he had succeeded in eliminating this from his measurements.

Laird and Muller, in their book on sleep,[6] report the results of metabolism measurements with subjects while solving multiplication problems. Apparently the technical details of their experiments were so inadequately controlled that one can not derive much of permanent value from their observations. The conclusion of Johnson and Weigand[7] in their digest of this book is more in line with our own findings.

In 1928 and again in 1931 Matsushima[8] reported the results of observations on the optimum atmospheric condition for mental effort. Unfortunately these reports are in Japanese, and we are unable to analyze them. In his annual report for 1930–31, Dr. Teruoka, Director of the Institute for Science of Labour at Kurasiki, Japan, gave a brief account[9] of the measure-

[1] Grafe, E., Bethe's Handb. d. normal. u. pathol. Physiol., 1928, **5**, p. 204.
[2] Chlopin, G. W., Jakowenko, W., and W. Wolschinsky, Arch. f. Hygiene, 1927, **98**, p. 164.
[3] Schroetter, H., Monatsschr. f. Ohrenheilk. u. Laryngo-Rhinologie, 1925, **59**, p. 1.
[4] Tigerstedt, R., Arch. néerl. Physiol., 1922, **7**, p. 538.
[5] Benedict, F. G., and A. Johnson, Proc. Amer. Philos. Soc., 1919, **58**, p. 89.
[6] Laird, D. A., and C. G. Muller, *Sleep: Why we need it and how to get it*, New York, 1930.
[7] Johnson, H. M., and G. E. Weigand, Psychological Bulletin, 1931, **28**, p. 480.
[8] Matsushima, S., Journ. Sci. Labour, Kurasiki, Japan, 1928, **5**, p. 657; *ibid.*, 1931, **8**, pp. 641 and 673.
[9] Teruoka, G., Annual Report, Inst. Sci. Labour, Kurasiki, Japan, 1930–1931, p. 18.

ments by Matsushima of the oxygen consumption during mental effort, and in 1932 Matsushima published, in English, the details of these measurements.[1] The Krogh spirometer was used. After the usual 30 minutes of repose the subjects (post-absorptive) had their metabolism measured, while lying, during 15 minutes of rest and then 15 minutes of mental effort. Ten men (20 to 36 years) and seven women (15 to 24 years) were studied. The mental effort for the men consisted in listening to the reading of an ethical treatise, the substance of which they attempted to repeat at the end of the test, and in adding 2-digit numbers at intervals of 6 to 12 seconds. The women performed simple mental additions. With both sexes Matsushima found, in general, increases in pulse rate, respiration rate and oxygen consumption. The oxygen consumption of the men (measured at 25° C.) increased on the average 5 per cent during mental effort. That of the women increased much more, the average increase being 12 per cent at 25° and 7 per cent at 20° C. The humidity of the atmosphere was little more than 70 per cent in the experiments with the men and over 80 per cent in those with the women. Matsushima concludes that the temperature and the humidity of the atmosphere influence the rate of oxygen consumption and its increase caused by mental effort. Thus these Japanese experiments suggest that mental effort has a rather pronounced effect on metabolism.

The Russian physiologist Chlopin and his associates presented papers in 1922,[2] 1925[3] and 1927,[4] in which they reported that they had noted considerable increases in oxygen consumption during mental effort. From our standpoint the most important feature of this Russian research is the fact that, relatively, the greatest effect was produced by arithmetical calculations and not by reading. In the earlier studies dealing with mental activity, the reading process was one of the more popular methods of attempting to secure mental effort. We are indebted to Professor Chlopin and his pupils for our own determination to concentrate in our investigation upon problems in mental arithmetic.

In a recent article by Rosenblum,[5] information is given regarding the findings of other Russian investigators, who have published their reports in publications inaccessible to us. Thus Rosenblum states that Slowzow and Rubel[6] found increases in oxygen consumption as a result of mental effort amounting to 12.6 and 18.8 per cent on the average, and that Miloslawsky and Plotnikowa[7] noted an increase in energy consumption of from 3.8 to 56.6 per cent. In experiments repeated on the same individual in which the same work was performed each time, Miloslawsky found marked fluctuations in metabolism and, indeed, in the reverse direction, namely, a *decrease in the gaseous exchange*[8] and the energy consumption during the period of mental activity. Molt-

[1] Matsushima, S., *Oxygen consumption during mental work*, Report No. 8, Institute for Science of Labour, Kurasiki, Japan, 1932.

[2] Chlopin, G. W., and J. L. Okunewsky, Arch. f. Hygiene, 1922, **91**, p. 317.

[3] Chlopin, G. W., *Hygienische u. biolog. Abhandlungen zum siebzigsten Geburtstag H. Griesbach*, Giessen, 1925, p. 22.

[4] Chlopin, G. W., Jakowenko, W., and W. Wolschinsky, Arch. f. Hygiene, 1927, **98**, p. 158.

[5] Rosenblum, D. E., Arbeitsphysiologie, 1932, **6**, p. 214.

[6] Slowzow and Rubel, Russk. fiziol. Z., 8. Ausg. 1–2, 51 (1925). (Cited by Rosenblum.)

[7] Miloslawsky and Plotnikowa, Westnik Kasanskogo Instituts der wissenschaftlichen Organisation der Arbeit, 1930. (Cited by Rosenblum.)

[8] One is reminded here of the present-day interest in that elusive "negative phase" in metabolism, alleged to be found by some recent writers.

schanova and Eshowa,[1] employing the Schaternikow technique, found that the reading of scientific articles in a foreign language caused an increase in oxygen consumption averaging 13 per cent. But Rosenblum points out that in these experiments the subjects had been engaged in their usual work and had even eaten three or four hours previous to the measurements and that these facts are not sufficiently taken into account by the investigators. These three Russian studies are in accord with the recent Japanese research in indicating a considerable effect of mental effort on metabolism.

Simultaneously with the Nutrition Laboratory's research on metabolism during mental effort undertaken in the spring of 1930 (a preliminary report of which was given before the National Academy of Sciences on April 28, 1930, and shortly thereafter published in the Proceedings of the Academy[2]), Rosenblum in Smolensk was carrying out his carefully arranged series of studies on the same theme.[3] Much of his technique was devoted to skilful and successful efforts to avoid difficulties with the use of the mouthpiece and to assure that the subjects were properly trained and accustomed to the experimental conditions prior to the metabolism measurements. The metabolism was measured in 10-minute periods, first, during repose, then during mental effort, and immediately thereafter during repose. In the majority of instances the subject engaged in mental effort for 30 minutes before the 10-minute period of actual measurement during intellectual activity began. Four experiments with more prolonged mental effort (2 hours) were also made. Rosenblum's protocols show that his technique was extraordinarily careful, and one can have only praise for them. His findings for the most part confirm our own, but a feature that appeared frequently in his experiments in striking contrast to our experiments was a decrease in the pulse rate during mental effort. Rosenblum concludes that mental effort *per se,* excluding spontaneous muscular contractions and movements, has no noticeable effect on the total energy consumption and that, from the standpoint of the physiology of work, intellectual activity can not be comprehended by the determination of the gaseous exchange. Although not attempting to analyze in detail the causes of the contradictory conclusions reported in the earlier literature, Rosenblum suggests that possibly the emotions accompanying the respiration experiments played a certain rôle and had no less effect than the mental effort itself. We feel constrained here to comment upon the extraordinary care used by Rosenblum in surveying the literature on this subject. Although at a great distance from large centers, he undoubtedly made a most careful study of all the earlier research and profited thereby in the arrangement of his own experiments. The fact that the preliminary report of our investigation, although published two years before his own material was finally published, had not reached him is not at all surprising.

[1] Moltschanova and Eshowa, Z. eksper. Biol. (russ.) **14**, Ser. A, No. 37, 1930. (Cited by Rosenblum.)
[2] Benedict, F. G., and C. G. Benedict, Proc. Nat. Acad. Sci., 1930, **16**, p. 438.
[3] Rosenblum, D. E., *loc. cit.*

GENERAL CONCLUSIONS DERIVED FROM A REVIEW OF THE LITERATURE

The conclusions that can be drawn from an examination of the previous literature on the metabolism during mental effort are of two kinds. Those derived from the general picture presented by all the experiments up to 1928 have been admirably summarized by Grafe. He concludes that there is no demonstrated influence of mental effort as such upon metabolism, but that there may be a secondary effect produced as a result of alterations in the mechanics of ventilation and a certain amount of muscular tonus. One must recognize that this conclusion is based both upon the results of experiments carried out in laboratories of good scientific standing in which pronounced effects of mental effort have been noted, and also upon the results obtained in many other laboratories which show almost no influence of mental effort. This view held by Grafe was also expressed by Benedict and Carpenter in 1909, namely, that mental effort has no appreciable influence upon metabolism. All of the researches subsequent to 1928 in both Japan and Russia (with one exception) show the previously experienced variability in metabolism with mental effort, with a new factor of a decrease at times in the metabolism as a result of mental effort. On the other hand, Rosenblum's careful experiments accord with the opinion that mental effort has no appreciable influence upon metabolism. It is thus seen that even in the more recent work there is a striking division of opinion on this important point.[1]

A second and far more important conclusion to be drawn from an examination of the literature deals with the pitfalls to be avoided in planning further experiments, pitfalls now obvious in many of the earlier researches. For example, analysis of the results of Benedict and Carpenter makes it clear that one experimental period of 3 or 4 hours' duration is much too long when one is studying the effect of as subtle a factor as mental effort. Moreover, the baseline should certainly approximate the basal metabolism, that is, it should represent the lowest possible metabolism that can be found with normal man, for upon this baseline is to be superimposed the effect of a factor which is probably very small, if not really insignificant. Since recent studies have shown that sleep and, indeed, drowsiness have a pronounced effect upon the respiratory exchange, experiments in which either of these factors is present can not be considered as conclusive. Hence, although ideally the lowest baseline should be secured in order to enhance the effect, percentagewise, of any increment in metabolism that may be caused by mental effort, practically measurements made during sleep can not be used and drowsiness must be avoided.

The type of mental effort to be studied must be carefully selected. A survey of the literature is convincing that the reading of ordinary or of more pro-

[1] Rounds, Schubert, and Poffenberger (Journ. Gen. Psychol., 1932, 7, p. 65) state that "mental work causes an increase of 61.2 c.c. of oxygen per minute or 28.8 per cent." Unfortunately the article by these investigators came to our attention too late to be critically analyzed here. The experiments were made with only one individual and the results show great irregularities, so great that the authors feel justified in using an average basal value of 212.7 c.c. of oxygen, from which they compute the increments for each day. R. A. McFarland ("The psychological effects of oxygen deprivation—anoxemia—on human behavior," Arch. Psychol., 1932, No. 145, p. 49) considers that the data of Rounds, Schubert, and Poffenberger show that "intense mental effort requires greatly increased energy."

found text matter and the memorizing of nonsense syllables or of prose do not represent such intense mental effort, at least so far as subjective impressions are concerned, as do arithmetical calculations. The calculations employed have varied from the solving of the simplest mental arithmetic problems to the computations necessary in complex geometrical problems and calculations in higher mathematics. If the mental effort is confined to problems in higher mathematics, the investigator is limited immediately in the number of subjects that will be available, since relatively few persons are capable of this type of mental effort. The study of the effects of mental effort should be carried out, however, not with one or two individuals, but with several. Consequently we believe that the type of mental effort best suited to this study is the solution of simple mental arithmetic problems, inasmuch as almost any intelligent person is capable of doing such problems with a reasonable degree of success.

Another point to be taken into consideration, as emphasized by the earlier researches, is the demonstrated influence of mental effort upon the heart rate. All known errors in recording the heart rate must be avoided. The subjects must not record their heart rates themselves. Preferably this observation should be made unknown to the subject. In many instances an increased carbon-dioxide exhalation during mental effort has been noted. This increase is probably accompanied by a disturbance in the mechanics of ventilation, which results in a sweeping out of carbon dioxide. A simultaneous study of the mechanics of ventilation is therefore important, if it is feasible to carry it out. The subject should be as nearly as possible in complete muscular and psychical repose. Every effort must be taken to secure a comfortable body position leading to the greatest degree of relaxation. It is also desirable, if possible, to have the experiment include observations during simple "attention" on the part of the subject, so that a comparison can be made of the metabolism in the different stages of complete mental rest or mental vacuity (but *not* during sleep or drowsiness), attention, and mental effort.

The dynamic attack may conceivably deal with measurements of skin temperature, body temperature, or temperature of the blood going to and from the brain (as exemplified particularly by the discussion of Gley), or observations of the pulse rate alone. Aside from measurements localized near the center of cerebral activity, the brain, these other measurements of pulse rate or body temperature in general reflect the large, pooled activities of the entire body. Hence an experimental procedure is necessary in which the baseline is first established, and then the effect of the mental effort superimposed upon this baseline is studied. In other words, the differential method is absolutely necessary. With humans a study of the composition of the blood going to and from the brain is ruled out. Measurement of the temperature of the blood going to and from the brain is likewise practically ruled out, although thermo-junction needles might be used. It would appear therefore as if the most profitable line of research would be that in which measurements are made, by the differential method, of the total metabolism or the total heat production. An analysis of the earlier researches shows considerable differences in the increments in metabolism ascribed to mental effort, but apparently in the more careful investigations very slight increases were found,

perhaps of the order of 5 per cent. Hence in the measurement of the metabolism during mental effort, 95 per cent of the noted oxygen consumption or heat production would represent the basal metabolism and only 5 per cent, at the most, the effect of the mental effort. The importance of ruling out, in so far as possible, every extraneous factor when the basal metabolism is being determined can not be over-emphasized. It is equally important to have no extraneous factor other than the mental effort appear in the periods when mental effort is superimposed on the baseline.

It would lead us too far afield to attempt to cite and discuss the literature dealing with the extreme variations in pathological cerebral activity noted in cases of great psychical excitation, on the one hand, and in cases of extreme mental depression and stupor, on the other hand. We shall content ourselves, therefore, only with a consideration of the influence of mental effort upon the metabolism of normal, healthy, intelligent men and women.

PLAN OF RESEARCH

FACTORS, SUBJECTS, AND MENTAL STATES CONSIDERED

Factors studied—In the plan of our experiments, profiting from the experience of Benedict and Carpenter and other investigators, we decided to study primarily the effects of mental accomplishment upon the heart rate, the mechanics of respiration, the carbon-dioxide exhaled, the oxygen absorbed, and the apparent respiratory quotient. Extraneous activity, if any, was to be recorded and the heat production was to be calculated from the measured oxygen absorption. The observations on the mechanics of respiration dealt particularly with the respiration rate per minute and the volume of inspired air per minute. In addition, a few measurements were made of the skin temperature of the forehead and of the insensible perspiration during mental effort. Blood-pressure measurements were not made. Although this is definitely a missing factor, our previous experience in mental effort experiments led us to expect little, if any, change in blood pressure.

Subjects—From our review of the literature, we believed that if mental effort had an effect upon the basal metabolism, it would in all probability be slight and that therefore any irregularities in the measured baseline caused by novelty of the experience would be confusing in comparisons of basal metabolism with metabolism during mental effort. Hence in selecting our subjects, we endeavored to obtain individuals well trained in metabolism measurements. In addition, we desired to have subjects capable of sustained intense mental effort, so that we might note whether the mental effort had a cumulative effect upon the metabolism. Since it has been our experience that college students, although willing to cooperate in physiological research, are considerably restricted in freedom of time, we also decided to secure individuals who could readily adjust their program so that the time of their arrival and their length of stay at the Nutrition Laboratory would meet any changing requirements of the tests. With these objects in view we finally selected six men and one woman to serve as subjects. Of the men, five (subjects I to V, inclusive) were university trained and two (subjects III and IV) had the rank of a college professor. Subject A and subjects II, IV, and V had had long experience with respiration experiments at the Nutrition Laboratory, and the last two were senior members of the staff. Subjects I, III, and VI were unaccustomed to the techniques used at the Nutrition Laboratory. Subject A was used primarily to perfect the general routine of the experiments. He was an especially well-trained subject, since more metabolism measurements had been made upon him than perhaps on any other man. He was not particularly adept in mental arithmetic, however, since his profession as an artist's model had not called for any special training in computations. His cooperation was perfect, but the experiments with him are to be looked upon chiefly as orientation experiments. The woman (subject VI) had been an accountant and was very intelligent. None of the men were particularly trained in mental arithmetic, but one (subject II) who had been on the laboratory staff for some time as chemist, was exceptionally adept at figures. In view of the mental qualifications of these in-

dividuals and the fact that they were all apparently in good health, we considered that their normality could not be questioned. Subsequent analysis of the physiological factors measured under basal conditions (see page 65) demonstrated that they were normal physiologically in every respect.

Basal conditions—Since it seems reasonable to suppose from the experience of earlier workers that the metabolism is but slightly increased by mental effort, we considered it highly important to study our subjects under conditions such that the baseline metabolism upon which the effect of the mental effort was to be superimposed should be as low as was consistent with the comfort of the subject and the regularity of heat production and at the same time such that the subject's brain should be capable of instantaneous acceptance of suggestions and problems. Sleep was therefore ruled out, but the subjects were studied in the post-absorptive condition, about 12 hours after food, and the last meal was supposed not to have been particularly high in protein content. In a few experiments two of our subjects were sitting, but in the majority of the experiments our subjects were lying, since it was considered that the lying position could be retained for the longest time with the greatest degree of comfort and relaxation. Every effort was made to have the subjects comfortable. When sitting, they were well supported with cushions[1] and the feet and legs placed so as to have the least possible strain upon them. This sitting position, when due care is taken to secure greatest comfort, has been found to result in a metabolism but slightly increased above basal.[2] If the room was cool, the subject was covered with a blanket. The room was well illuminated whenever the arithmetic problems were not given verbally but had to be read from typed sheets by the subject. In every way we attempted to secure the greatest degree of comfort for the subject.

Mental states—Since we purposed carrying out our research by a differential method, we felt that it was ideal for the subjects to be, first of all, in a state of what might be termed "mental vacuity," that is, thinking of nothing. Yet it was not possible to permit them to sleep, for this would have necessitated their awakening from sleep, readjusting themselves to the environment and beginning immediately to solve fairly complicated mental arithmetic problems. The subject was therefore encouraged to lie or sit quietly without thinking of anything in particular and to have the mind more or less wandering. This state was assumed to approximate mental vacuity. We next endeavored to secure a state of "attention" unaccompanied by real tension. Special efforts were made to measure the metabolism of the subjects in this state, for we wished to determine whether the intermediate mental step of passing from mental vacuity to "attention" involved any measurable metabolic process. (See page 27 for details of the technique employed to obtain "attention" on the part of the subjects.) The third stage was to measure the metabolism during sustained, intense mental effort. It was not considered satisfactory to limit these measurements to a 3- or 4-minute period, since it was believed that in such a short length of time the mental effort would be only of a transitory nature. The subjects were therefore required to be mentally active for several consecutive 15-minute periods,

[1] The sitting position shown in Plate 1, page 30, was that assumed for the photograph only and is not illustrative of that assumed by our subjects in the actual experiments.

[2] Emmes, L. E., and J. A. Riche, Amer. Journ. Physiol., 1911, 27, p. 406.

usually totaling one hour. It was believed that in this longer length of time, the mental effort would be sufficiently pronounced for its effect upon the metabolism to be measurable, provided there were any effect. Moreover, the sustaining of mental effort for a protracted period made it possible to note whether the metabolism was affected by such factors as training and onset of fatigue. Thus it was conceivable that in the fourth consecutive 15-minute period of a 1-hour measurement the element of fatigue might play a greater role than in the first 15-minute period.

Types of mental effort required—To secure real, sustained mental effort and thus bring our measurements as nearly as possible into the field of psychodynamics, we employed three methods. One method (employed only in one experiment with subject VI) consisted in giving the subject simple problems in addition. Sheets of these problems had already been specially printed and used for another purpose in an earlier investigation.[1] Digits were arranged in blocks of one hundred. The type was 12 point. The digits 1 and 0 were not employed, and an effort was made to avoid combinations which added to 10. The blocks were arranged in ten columns, each containing ten digits. A page was composed of eight blocks, and five different pages were available. One of these pages was placed solidly in front of the subject, in good illumination. The subject mentally added each column vertically and then added the digits in each line horizontally. When she had made the additions both vertically and horizontally, she pressed a telegraph key and a second page of problems was placed before her. The answers to the problems were not written on paper or spoken, and there was no control of the accuracy of the additions. We were not interested in the accomplishment of the task with the greatest degree of accuracy, and it made relatively little difference whether a slight error was made or not. The subject was asked to be conscientious and endeavor to add correctly. In order to have controlled the accuracy of the results it would have been necessary for the subject to write or speak the answers, and it seemed best not to include this muscular work in the tests. Our second method of inducing mental effort was patterned after the unusually successful procedure followed by Chlopin and his associates. We were fortunate in securing in a personal letter from Dr. Jakowenko some typical problems given in their studies, mental arithmetic problems such as are commonly given in school. One of our subjects was asked to solve a series of similar problems, selected from an arithmetic text-book. These two methods were employed chiefly in orientation experiments, but for severe mental tension still a third type of problem was used, namely, the multiplication of two numbers, usually a 2-digit by a 2-digit number. Any reader who is not convinced of the intensity of such mental effort has but to close the eyes for a few minutes and carry out mentally four or five operations of multiplying two sets of figures, such as 74 times 49 or 53 times 84. The direct effect will be felt within one or two minutes. The reader should then recall that many of our measurements during mental effort continued for *one hour*, at the end of which time each subject was conscious of pronounced mental fatigue amounting at times almost to confusion. These multiplication problems were selected at random.

[1] Benedict, F. G., Miles, W. R., Roth, P., and H. M. Smith, Carnegie Inst. Wash. Pub. No. 280, 1919, fig. 19, p. 143.

Indeed, the first problems were improvised by the operator as the experiment progressed. To some extent the problems were scaled in their degree of difficulty by the seeming time response of one of our subjects (A), who was not particularly versed in arithmetic problems. A problem was given, and if the reaction was slow or the subject appeared confused, the tension was relieved by giving next a simple multiplication, such as 7 times 9. This was then followed by a problem of the usual degree of difficulty. One of our subjects (II) was adept enough to multiply mentally a 3-digit by a 2-digit figure. (See page 58.)

Measurement by mechanical means of degree of attention and of mental accomplishment—In the periods of so-called "attention," the subject was required to press a telegraph key lightly with the second finger of the right hand when an electric light appeared in the field of vision. Two small electric signal lamps were used, one white and one red. The subject was expected to press the telegraph key once when the white light appeared and twice when the red light appeared. It was believed that the subject's attention might lag if only one light was used, but that if two lights of different colors were used, he would have to be more on the alert to discriminate between the two colors. Under such conditions any error in his signals would indicate lack of attention. The lamps were lighted intermittently by chance by the operators who were in the room, each operator, whenever he passed by the telegraph keys connecting with the lights, touching whichever one of them he felt inclined to touch. In general the contact with one or the other of the lamps was made about once every 20 seconds, frequently once every 10 seconds. A triple signal magnet was arranged to record on a slowly moving kymograph drum which colored light had appeared and the signals given by the subject in response to the appearance of the colored lights. This device enabled a direct measure of the degree of attention of the subject and likewise served as an index of the moderate amount of discrimination that he had to employ. These records showed that there was invariably no lack of attention or of discrimination, and thus furnished definite proof that our subjects were mentally alert throughout the entire "attention" period.

Further use was made of this system of signal magnets when the problems in mental arithmetic were given. In this case the rate of rotation of the kymograph was somewhat more rapid. One of the contacts connecting with the telegraph key was pressed by the operator when the last syllable of the sentence stating the problem was pronounced. Then the subject attempted to solve the problem and pressed another key when he considered that he had solved it. The signals of both the operator and the subject were recorded on the kymograph, and from the kymograph curves the length of time required to solve the particular problem could be determined. At first it was our intention to analyze these curves to note the time reactions to the various problems, in order to discover whether there was any facilitation in the solution of the problems as the experiment progressed, whether there was any apparent fatigue at the end of an hour and, since the same problems were used repeatedly, whether there was any memorization. It soon became apparent that the problems solved during an experiment were many, from 40 to 80 per 15-minute period, and hence this final analysis was not considered necessary. It is admitted, however, that this phase of our work was poorly

done. Undoubtedly the trained psychologist would have secured a great deal more out of it.[1] The lack of uniformity in the difficulty of the problems was great, but since the number of problems solved per minute was large, the degree of difficulty of the problems from 15-minute to 15-minute period was on the average much the same. Hence the number of problems solved furnished probably a fairly true measure of the mental accomplishment. We had no control, however, upon the accuracy of the performance. Some of our subjects admitted that they did not attempt to complete, mentally, the multiplication of a 2-digit number by a 2-digit number, such as 79 times 63. The difficulty of recalling the first step in the multiplication (as 79 times 3) after the second step had been completed became so great that the element of irritability occasionally entered. Hence the subject oftentimes considered that he was multiplying 79 by 3 and 79 by 6, for example, and made no attempt to add the two results. One must therefore realize that this measure of the amount of mental effort accomplished, as indicated by the number of problems solved, is only relative. Our main object was to secure sustained intense mental effort to the extent of exhaustion, and since the problems were "fitted to the subject," varying considerably with each subject and not all comparable in severity, it seemed unjustifiable to attempt to measure the effect per unit of work or per problem.

Subjective impressions as an estimate of the severity of mental effort—With practically all mental workers reliance must be had upon the subjective impressions in estimating the severity of mental effort. It was clearly recognized that listening to a person reading makes the least demands for mental effort. Rosenblum, basing his conclusions upon subjective impressions, classified reading as light mental effort, memorizing of strange words and reading of scientific articles in foreign languages as moderately severe mental effort, and the solving of complicated calculations (with special emphasis laid upon the Bourdon test) as the most strenuous. As a result of the experience of Benedict and Carpenter, who noted little, if any, increase in metabolism with mental effort and found no definite proof of a difference in metabolism with the different types of mental activity engaged in by their students, we decided to require our subjects to undertake that type of mental effort which, in accordance with general belief, is the most strenuous, namely, mental calculations. Here again subjective impressions furnish the only means of measuring the degree of mental effort. All of our subjects, without exception, had the impression that they had been engaged in severe and sustained mental effort.

[1] An excellent illustration of interpretation of results from the psychological standpoint is the ingenious handling of somewhat similar experimental conditions by Golla and Antonovitch (Brain, 1929, 52, p. 491).

TECHNIQUES EMPLOYED

RESPIRATION APPARATUS

Although the results of this research as a whole have a far greater interest for psychologists than for physiologists, nevertheless one may properly take the ground that the results should not be published unaccompanied by a description of the techniques employed. Since the techniques were in many ways unique in attacking a problem of this kind, a certain amount of description is essential for the proper understanding of the experimental procedure. The most important feature of this study was naturally the determination of the respiratory exchange, primarily of the carbon-dioxide exhalation and the oxygen consumption, with likewise frequent measurements of the respiratory quotient. In selecting from the various Nutrition Laboratory techniques for the determination of the respiratory exchange that technique best suited for the study of the effects of mental effort, we had to meet several conditions. In the first place, as shown by the experience of other investigators, it was highly important that the subject should be, in so far as possible, in complete muscular repose and, at the time of the basal measurements, in complete mental repose, free from irritation and from annoying or distracting attachments. For practically all subjects this condition rules out the use of the usual mouthpiece, nosepieces, or face mask,[1] which interfere either with respiration or induce salivation, hamper vision, and are at best worn only for relatively short periods save by long- and well-trained subjects. In the second place, it was desirable not to confine the measurements to the study of the carbon-dioxide exhalation, but if only one gaseous factor was to be measured, to determine preferably the oxygen consumption. Ideally both factors should be measured, in order to note whether the respiratory quotient undergoes any change. In consideration of the previous experience of other investigators in using the carbon-dioxide measurement alone and the consensus of opinion that mental effort alters significantly the mechanics of respiration, we felt that determinations of both the oxygen consumption and the carbon-dioxide elimination were important, in order to obtain further evidence regarding the alteration in the mechanics of respiration and to note whether there is any particular tendency for a change in the respiratory quotient with mental effort that might be compared with the commonly accepted view that muscular work is accompanied by increased consumption of carbohydrate. Hence our selection of technique was based upon the desirability of determining both gaseous factors. The difficulty commonly encountered with breathing appliances was solved by using a helmet or head chamber. This is easily adjusted over the head with a light rubber collar around the neck, avoids all irritation of the mouth and nose, provides free vision, and, if necessary, can be worn with comfort for hours. Measure-

[1] The difficulties of studying psychological problems with a subject breathing through a mask or mouthpiece are emphasized by Golla and Antonovitch (Brain, 1929, 52, p. 491), who state that the "method is so liable to subjective variations as to be unsuitable for psychological work. By means of control tests we were able to demonstrate that even with carefully trained subjects any attempt to breathe through an open mouthpiece or mask, that is to say a piece of apparatus which centers the subject's attention on his breathing, invariably gives rise to an abnormal type of respiration, generally associated with hyperpnœa."

ıents of both factors of the gaseous exchange were made by employing this elmet with the spirometer type of respiration apparatus according to two ıethods, long in use and perfectly developed at the Nutrition Laboratory, ıat is, the closed-circuit and the open-circuit methods. A detailed descrip- .on of the helmet respiration apparatus in its various forms has recently een published.[1]

CLOSED-CIRCUIT APPARATUS

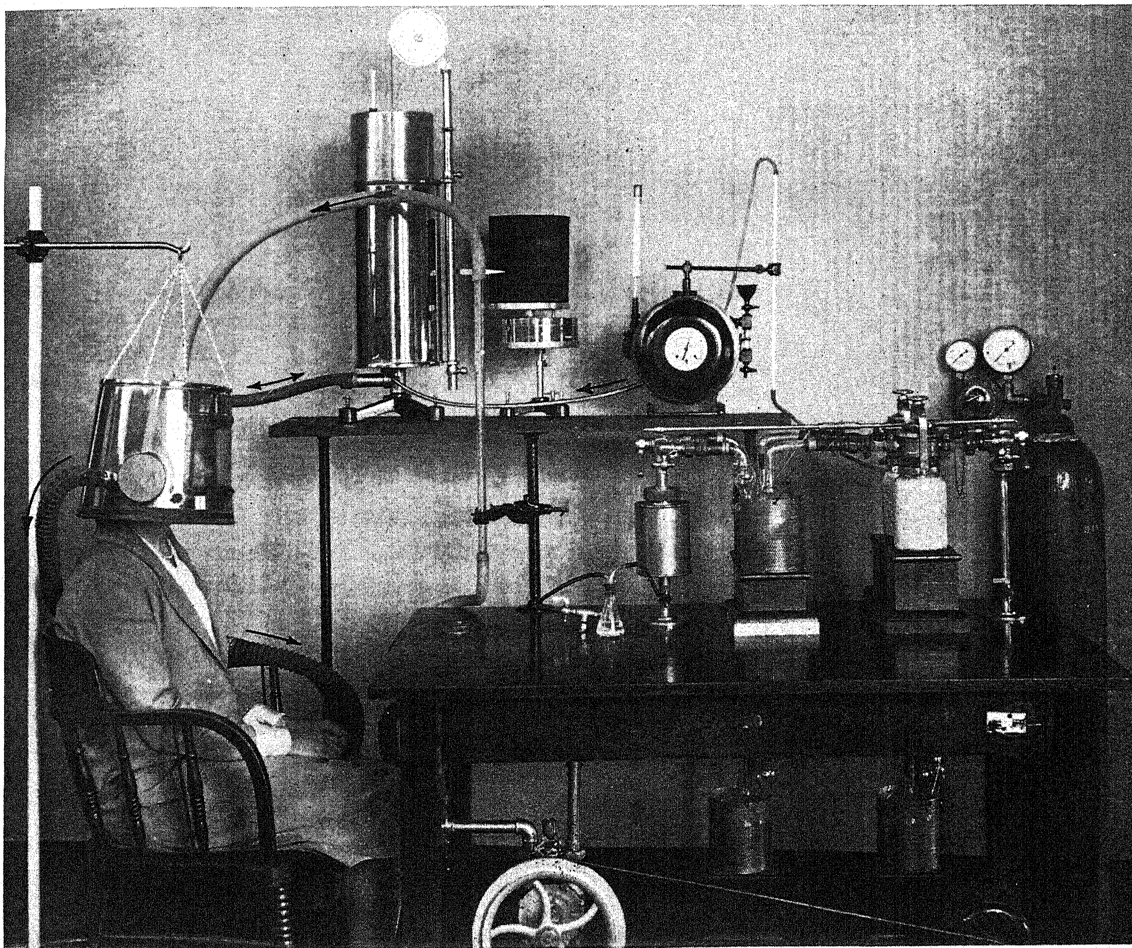
In the closed-circuit apparatus the helmet was in reality used as a small espiration chamber, connecting with a delicately counterpoised 6-liter pirometer to provide for free expansion and contraction of the air caused by espiratory movements, and ventilated by the well-known and long-applied niversal respiration apparatus.[2] The details of the closed-circuit ventilating ystem are shown in the photograph in Plate 1 and in the schematic drawing ı figure 1. The subject's head was enclosed in the helmet chamber with he head facing a small window. Air was withdrawn from the helmet hrough a corrugated rubber tubing at the back by a rotary blower, seen on he lower part of the table in Plate 1. This blower forced the air through wo bottles of sulphuric acid on the lower shelf of the table, where the water apor was removed, then (by proper turning of valves) through one of the wo sets of bottles on top of the table containing, respectively, soda-lime ınd sulphuric acid. Here the carbon dioxide and any water vapor given ıp by the soda-lime were removed, and the gain in weight of these last two ottles was taken as a measure of the carbon dioxide exhaled. The air next assed through a can of absorbent cotton sprinkled with dry sodium bicar- onate, where any acid fumes were removed. It then passed through a otamesser or flow meter (R_1, fig. 1), which indicated the rate of ventilation, ınd finally entered the top of the helmet. In most instances the air was eturned to the helmet dry, to aid in the vaporization of water from the ubject's face, thereby giving the face a sense of coolness and comfort inside he helmet. Occasionally the air was moistened somewhat before it entered he helmet by being passed first through a bottle of water. There was a lirect connection between the helmet and the spirometer, and by means of he pointer attached to the counterpoise weight of the spirometer the excur- ions of the bell caused by the respirations of the subject were written on a evolving kymograph drum.

This system, as shown in Plate 1 and fig. 1, was in principle the usual type of ıpparatus used for measuring the consumption of oxygen alone,[3] but since n this particular case it was desired to measure the carbon-dioxide elimina- ion also, the absorbing system was somewhat more complicated. The nethod employed to measure the oxygen consumption was to meter the olume of oxygen introduced into the spirometer from a cylinder of the ompressed gas by means of a carefully calibrated wet-gas meter, shown in Plate 1 on the stand above the table. Under these conditions the oxygen

[1] Benedict, F. G., Abderhalden's Handb. d. biolog. Arbeitsmethoden, 1933, Abt. IV, Teil 13,). 465.

[2] Benedict, F. G., Amer. Journ. Physiol., 1909, **24**, p. 345; *ibid.*, Deutsch. Arch. f. klin. Med., 1912, **107**, p. 156; *ibid.*, Abderhalden's Handb. d. biolog. Arbeitsmethoden, 1924, Abt. IV, Teil 10, p. 440.

[3] Benedict, F. G., New Eng. Journ. Med., 1930, **203**, p. 150.



THE HELMET CLOSED-CIRCUIT RESPIRATION APPARATUS AS USED IN MEASURING THE METABOLISM DURING MENTAL EFFORT.

The blower beneath the table withdraws the air from the helmet through the corrugated rubber tubing at the back, forces it through two sulphuric acid bottles beneath the table where the water vapor is removed, then through bottles of soda-lime and sulphuric acid on top of the table, where the carbon dioxide exhaled by the subject and any water vapor given up by the soda-lime are removed, next through a can of sodium bicarbonate which removes any acid fumes, through a rotamesser or flow meter, and back into the helmet at the top. The direction of the air current is indicated by the arrows. Oxygen is introduced into the system as needed, from the cylinder at the right, being metered by the wet gas meter and passing into the bottom of the spirometer. The excursions of the spirometer bell are traced on the kymograph by the pointer attached to the counterpoise weight of the bell. In actual experiments the apparatus was behind the subject, and the subject was usually lying.

was admitted exactly as fast as used by the subject, that is, at such a rate as to hold the kymograph tracings at a constant level throughout the period. By this means it was possible in experimental periods as short as 10 or 15 minutes to determine by weight the carbon dioxide exhaled and, from the meter reading, the oxygen consumed. From these two values the respiratory quotient was computed.

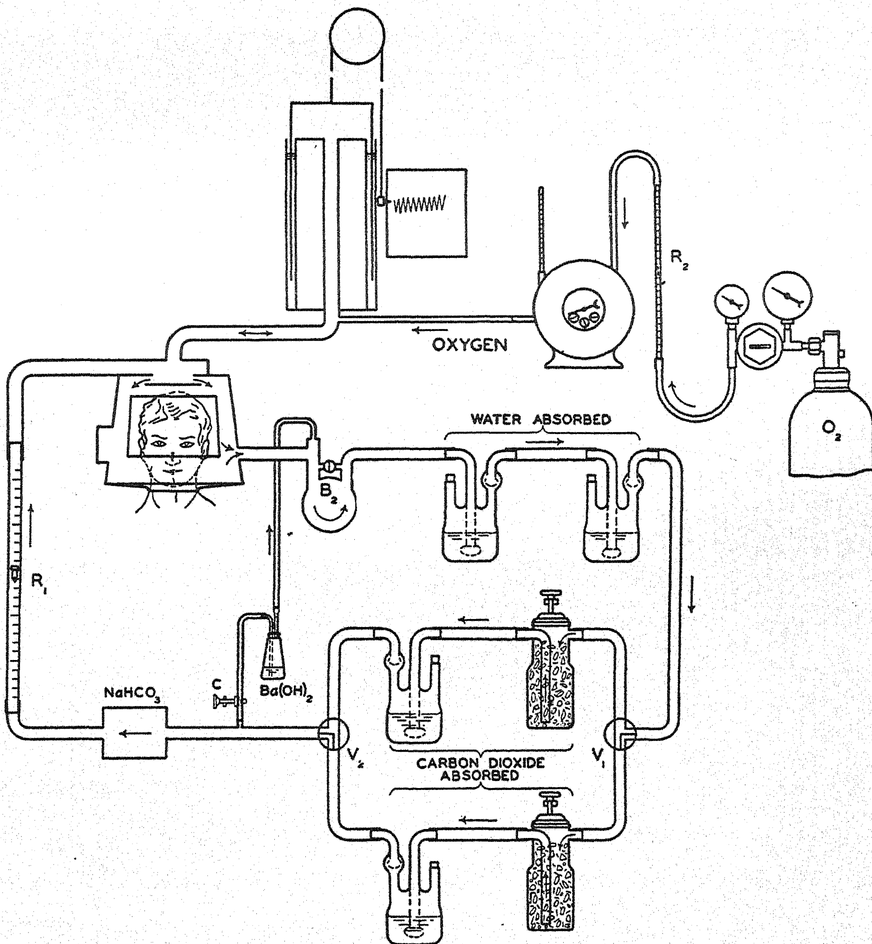


FIG. 1—SCHEMATIC OUTLINE OF HELMET CLOSED-CIRCUIT RESPIRATION APPARATUS.

B_2, blower; R_1 and R_2, rotamessers or flow meters; V_1 and V_2, valves for deflecting air current through one of two sets of soda-lime and sulphuric acid bottles; c, screw pinchcock allowing some air to pass through barium hydroxide and back to blower B_2.

OPEN-CIRCUIT APPARATUS

Although the uniformity in the respiratory quotients obtained by the closed-circuit method was such as to lend confidence in their accuracy, nevertheless for the specific study of the respiratory quotients it was desired to have another method of determining them. The development and perfection of

Carpenter gas-analysis apparatus[1] has made it possible to study the ratory quotient with a very high degree of accuracy. Consequently in e of our experiments the helmet apparatus was used on the open-circuit ciple in conjunction with the Carpenter gas-analysis apparatus, and the iratory quotients were determined by gas analysis (fig. 2 and Plate 2). door air was forced by a rotary blower, B_1, through a bottle of soda-lime, A, ree it of carbon dioxide, then through a rotamesser, R, or flow meter

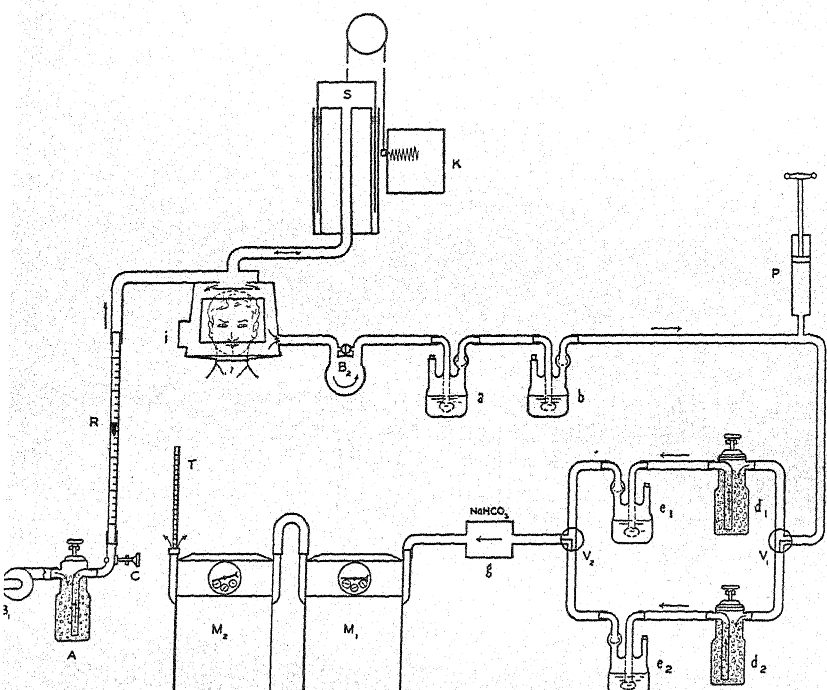
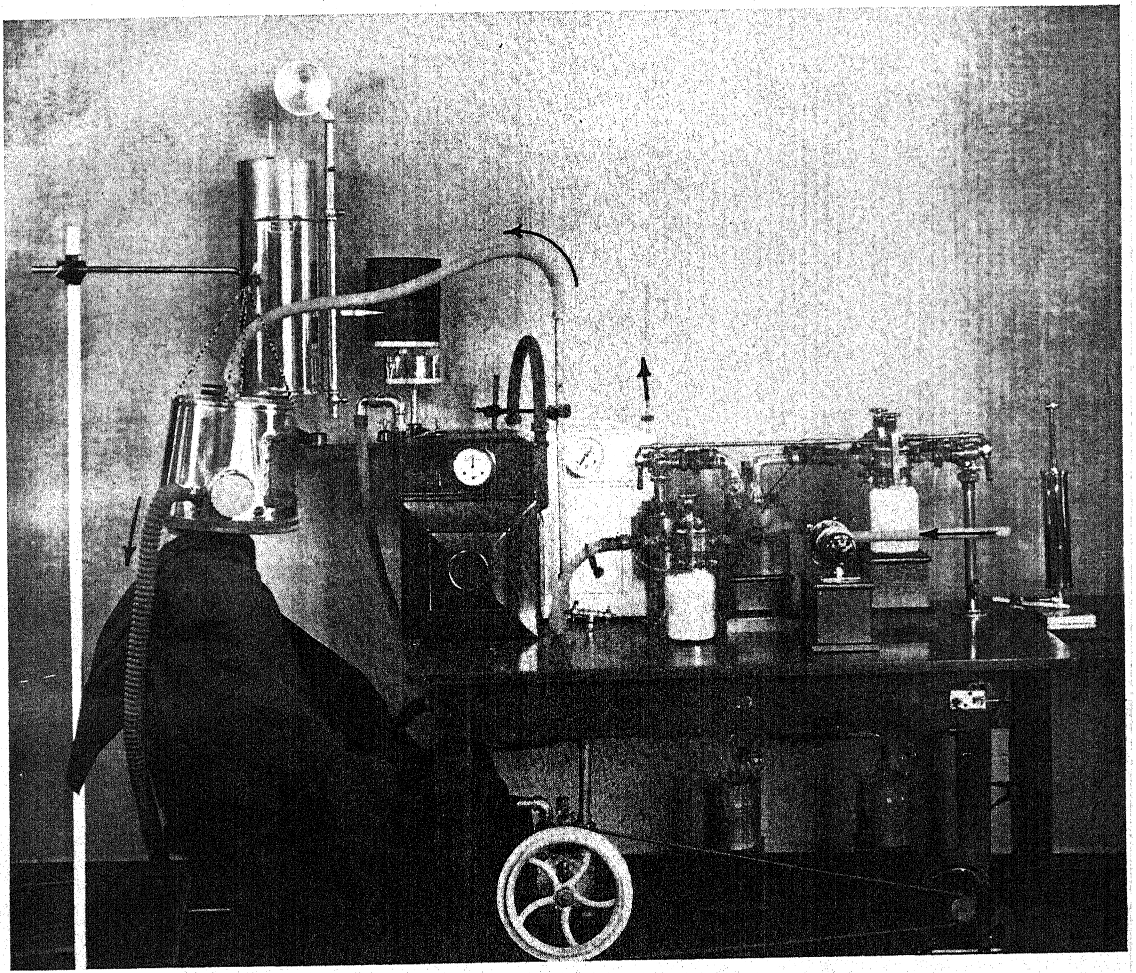


FIG. 2 —SCHEMATIC OUTLINE OF HELMET OPEN-CIRCUIT RESPIRATION APPARATUS.

and B_2, blowers; A, bottle of soda-lime; c, screw pinchcock to regulate inflow of air; R, nesser; a and b, vessels of sulphuric acid; P, pump for withdrawal of air sample; V_1 and V_2, es to deflect air into soda-lime and sulphuric acid vessels d_1 and e_1 or d_2 and e_2; g, can of um bicarbonate; M_1 and M_2, dry gas meters; T, thermometer; i, rubber-covered opening de of helmet; S, spirometer; K, kymograph.

ich aided in controlling the ventilation rate and particularly the position the spirometer bell), and then into the top of the helmet. The arrows icate the direction of the air current. The air was withdrawn from the net by a second blower, B_2 (beneath the table), and passed through two tles of sulphuric acid, a and b (also beneath the table), to dry it. From se bottles it passed up through the pipe at the right end of the table, and ample of it was drawn (dry) for subsequent gas analysis by a sampling np P (shown also at the right in fig. 2 and Plate 2), which connected with a cock in the upright pipe. The pump piston was withdrawn from the

[1] Carpenter, T. M., Abderhalden's Handb. d. biolog. Arbeitsmethoden, 1933, Abt. IV, Teil p. 593.



THE HELMET OPEN-CIRCUIT RESPIRATION APPARATUS AS USED IN MEASURING THE METABOLISM DURING MENTAL EFFORT.

Outdoor air is forced by the small blower on top of the table through a bottle of soda-lime to free it of carbon dioxide, through a rotamesser, and into the top of the helmet. The larger blower beneath the table withdraws the air from the helmet and forces it through two bottles of sulphuric acid beneath the table, where the water vapor is removed. The air then passes through the upright pipe at the right end of the table, through one of the series of soda-lime and sulphuric acid bottles where carbon dioxide and water vapor, respectively, are absorbed, through a can of absorbent cotton and sodium bicarbonate where any acid fumes are removed, and finally through two dry gas meters. A thermometer at the exit of the second meter indicates the temperature of the air as it escapes into the room. The spirometer (6-liter) acts as an expansion and contraction chamber, and the excursions of its bell are traced upon the kymograph at its right. A sample of the air from the helmet is withdrawn through the petcock in the upright pipe at the right by the sampling pump shown at the extreme right in the photograph. In actual experiments the subject was usually lying, and the apparatus was always behind him.

pump cylinder one-twentieth of its length every half minute. Thus the sample was drawn in several small portions throughout the period. Since the ventilation rate and the metabolism during any given period were uniform, it was believed that the sample thus drawn was in composition representative of the total volume of air passing from the helmet. Hence its percentages of carbon-dioxide and oxygen were directly ascribable to the carbon-dioxide exhalation and the oxygen consumption of the subject. The ventilation of the helmet was so adjusted that the carbon-dioxide content of the air leaving it was not far from 1 per cent, *i. e., circa* 20 liters per minute. Except for the sample withdrawn by the pump, the total ventilating air current from the helmet was then passed (by proper turning of valves V_1 and V_2) through one or the other of two sets of soda-lime and sulphuric acid bottles on top of the table (d_1 and e_1 or d_2 and e_2, fig. 2), where the carbon dioxide exhaled by the subject and the water vapor given up by the soda-lime were removed. The air then passed through a can of sodium bicarbonate (g, fig. 2), through two dry gas meters (M_1 and M_2, fig. 2) on the left corner of the table, and escaped into the laboratory room. Since the air passing through the meters was dry, it was necessary to record the temperature of the air only on a dry-bulb thermometer, T, at the exit point of the second meter. The barometric pressure also was recorded.

The open-circuit principle as thus employed is based upon the fact that the ordinary household dry gas meter is an instrument of precision, can be readily calibrated, and the true volumes calculated from its readings. Since carbon-dioxide-free air is supplied to the helmet and since the percentage of oxygen in outdoor air has been thoroughly established as constant at 20.940, analysis of the air leaving the helmet alone is necessary. From the results of the gas analysis were calculated the carbon-dioxide increment, the oxygen deficit, and the respiratory quotient. The difference in the meter readings at the start and end of the experimental period was increased by the volume of air withdrawn into the pump for gas analysis and by the volume of carbon-dioxide absorbed in the soda-lime. The total volume thus obtained was then corrected by the meter factor and reduced to standard conditions of temperature and pressure, and the results of the gas analysis were then applied to this final, corrected volume in order to calculate the oxygen consumption and the carbon-dioxide output. The carbon-dioxide measurement thus obtained was further controlled by passing the air, previously dried, through the weighed train of soda-lime and sulphuric acid bottles. The oxygen measurement obtained as described above was controlled by comparison with the result derived by division of the carbon-dioxide output as determined by weight by the respiratory quotient determined by gas analysis.

COMPARISON OF RESULTS OBTAINED BY CLOSED- AND OPEN-CIRCUIT METHODS

The use of the helmet in place of a mouthpiece or face mask made it imperative to demonstrate that this head chamber permitted measurements of the respiratory exchange with the greatest degree of accuracy and that any systematic error could not obscure the possibly very small effect of the superimposed factor of mental effort. Consequently comparison of determina-

tions of the oxygen consumption by two basically different methods (metering the oxygen admitted to a closed-circuit apparatus, on the one hand, and, on the other, metering in the open circuit the total volume of air ventilating the helmet and multiplying this metered volume by the oxygen deficit as determined by gas analysis) was considered an additional means of proving the accuracy of the methods. The close agreement of the results obtained by the closed- and open-circuit principles convinced us that both methods were sound and either could be employed. As a matter of fact, both were used, although the greatest stress was laid upon our open-circuit method, for theoretically at least we considered the respiratory quotient less liable to error when determined by gas analysis than when determined by the closed-circuit principle. The slightest leak in the helmet or in the system at any point when the closed-circuit method is used affects greatly the oxygen determination and naturally also the respiratory quotient. On the other hand, when the open-circuit system is used, a leak either into or out of the system can hardly be considered on any grounds as affecting the respiratory quotient as measured by gas analysis. A very considerable leak in the open-circuit system would, it is true, affect the measurement of the total metabolism, but our special emphasis was on the respiratory quotient, and a leak is without influence on the respiratory quotient. Subsequent alcohol control tests confirmed us completely in our belief in the accuracy of the apparatus.

From the standpoint of the determination of the carbon-dioxide output alone, it is obvious that weighing the total carbon dioxide exhaled is, theoretically at least, more accurate than applying to the metered volume the carbon-dioxide increment as obtained by gas analysis. Hence, since we determined the carbon-dioxide output by weight when employing the open-circuit as well as when using the closed-circuit method, we have reported the carbon-dioxide values on this basis in all the tables that follow. The oxygen values recorded in the tables are, in the case of the experiments by the closed-circuit principle, those obtained by metering the volume of oxygen introduced into the system. In the experiments by the open-circuit principle, the oxygen values represent those obtained by division of the carbon-dioxide value as obtained by weight by the respiratory quotient as determined by gas analysis.

In the open-circuit type of apparatus the excursions of the spirometer bell were extremely irregular, depending in large part upon the delicate balance between the blower furnishing air to the helmet and the blower withdrawing air from the helmet. By continuous manual control of the air entering the helmet it was possible to maintain the excursions of the spirometer bell nearly the same. This was not, however, our particular desire and such control was not commonly undertaken.

Practically all our experiments were made with the subjects lying. To make the photographs somewhat more compact, the subject is shown sitting in Plates 1 and 2, and also facing the apparatus. In actual experiments the apparatus, including the spirometer, was behind the subject and there was no person and no movement of any kind in his field of vision to distract his attention. The rubber-covered opening at the side of the helmet enabled the subject to hear easily the spoken problem.

ALCOHOL CONTROL TESTS

Although this study of the metabolic effect of mental effort is based primarily upon the differential method and any slight systematic error would apply in both the repose and the mental effort periods, we felt that the usual practice of the Nutrition Laboratory in making the control experiments must here also be carried out. These controls are the usual alcohol check tests. The accuracy of both the open- and the closed-circuit apparatus was confirmed by a series of tests in which a known amount of burning ethyl alcohol resulted in the production of a known amount of carbon dioxide and the absorption of a known amount of oxygen. To make an alcohol control experiment with the helmet respiration apparatus is not simple. When the helmet was first developed, a large number of such tests were made with it, both in conjunction with the closed- and the open-circuit form, and it was only when the entire equipment gave satisfactory results that we deemed it ready for use in experiments on mental effort. From the standpoint of the respiratory quotient alone as determined by the open-circuit principle, one could insist that a sample of the air current when alcohol was burned in the apparatus should give on the gas-analysis apparatus a quotient of not far from 0.666. But our control went much further than this. It was necessary that our apparatus show in an alcohol control test not only a respiratory quotient of approximately 0.666 but that the amount of carbon dioxide and the amount of oxygen calculated from the meter readings should agree with the theoretical amounts computed from the known volume of alcohol burned during a given time. Moreover, in the case of the open-circuit apparatus (fig. 2) the weighed amount of carbon dioxide collected in the soda-lime bottle should agree with the amount determined by gas analysis referred to the meter readings. These controls were invariably most satisfactory.

MECHANICS OF RESPIRATION

Our main index of whether there is uniformity in the mechanics of respiration is obtained from the kymograph records of the excursions of the spirometer bell. With the closed-circuit apparatus, oxygen could be admitted to the system at precisely the same rate at which it was used, and hence the spirometer tracings were held at practically a constant level. In the open-circuit type, owing to the difficulty of obtaining perfect equilibrium between the supply of outdoor air to the helmet and the withdrawal of air from the helmet, the spirometer tracings were invariably irregular. The spirometer was employed simply as a null instrument in this case, to hold the volume of incoming air approximately constant. The curves obtained with the closed-circuit type of apparatus therefore furnish more reliable information regarding the mechanics of respiration than do those with the open-circuit apparatus, and the records by the open circuit serve only as a rough confirmation of the findings with the more sensitive spirometer system employed in the closed circuit.

In figure 3 are reproduced two curves showing the kymograph tracings of the excursions of the spirometer bell in two experimental periods with subject VI when the helmet was used as a closed circuit and oxygen was introduced at a rate sufficient to maintain the bell at a constant level. The upper curve

is typical of curves obtained in rest periods and the lower one of those in periods of mental effort. The upper curve may also be said to be typical of those obtained during attention, since inspection of all the graphic tracings confirms us in the belief that the mechanics of respiration during attention is the same as that during mental repose.

From these kymograph curves as obtained both by the open- and by the closed-circuit method, we have calculated the respiration rate and the volume of ventilation of the lungs per minute and have recorded the results in the following tables. With a millimeter scale, a measurement was made of the perpendicular distance represented by each set of up and down strokes of the spirometer pointer, *i.e.*, the tracing of each inspiration and expiration of the subject. The sum of these measured perpendicular distances for each

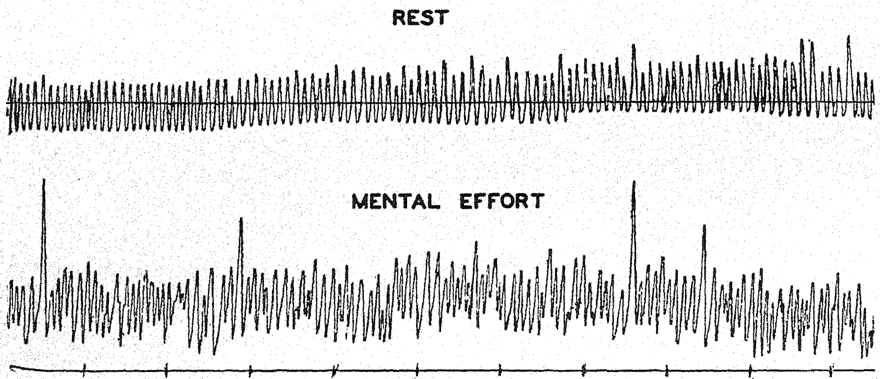


FIG. 3—TYPICAL KYMOGRAPH TRACINGS OF THE EXCURSIONS OF THE SPIROMETER BELL OBTAINED IN EXPERIMENTS WITH THE HELMET RESPIRATION APPARATUS ON THE CLOSED-CIRCUIT PRINCIPLE.

The upper curve was obtained with subject VI during a period of mental repose and the lower curve during a period of mental effort. Oxygen was introduced into the closed system at such a rate as to hold the spirometer bell at a constant level. The horizontal line below the curves is marked off into minutes by the short vertical lines. Only portions of the curves for the periods and not the complete curves are here shown.

experimental period was multiplied by the factor representing the volume in cubic centimeters per millimeter length of the spirometer bell. The total cubic centimeters thus obtained, measured saturated at the temperature of the spirometer, were converted to liters, reduced to 0° C., dry, and 760 mm.,[1] and divided by the length of the period in minutes to obtain the liters of apparent ventilation per minute.

The results thus obtained may be considered only as of relative value, since the total depth of respiration was not completely recorded by the kymograph tracings. For example, if the subject actually inhaled 500 c.c. of air, the volume according to the kymograph tracing might amount to only 400 c.c. This is explained by the fact that unless extraordinary care is taken to eliminate the slack in the rubber diaphragm making the closure between the helmet and the subject's neck, this give or slack will allow a contraction or distention of the diaphragm of at least 100 c.c. with each respiration, so

[1] Carpenter, T. M., Carnegie Inst. Wash. Pub. No. 303A, 1924, tables 7 and 8, pp. 39 to 70.

that the complete respiratory movement as traced on the kymograph is too small. In these experiments towels were placed between the subject's shoulders and the under side of the rubber diaphragm in an attempt to avoid this slackness in the diaphragm, but nevertheless a certain degree of flexibility was necessary. No definite correction for this factor, however, can be applied to the volume of ventilation as measured on the kymograph record. For instance, one can not say that the volume thus measured should be increased by one-fourth. Furthermore, in all probability such a correction would vary with different individuals, depending upon the size of the neck and the slackness of the rubber. We have assumed that the up-and-down motion of the rubber diaphragm remained essentially constant on any given day and probably did not vary greatly from day to day with the same individual. Of these two assumptions only the first is of importance in our comparisons, as we were interested primarily not in the absolute values but in the relative values for the mechanics of respiration during periods of mental repose and mental effort on any one day, and we felt that the tracings thus secured would be satisfactory. Since subsequently it was noted that there was a definite increase in the ventilation of the lungs during mental effort, it is perhaps to be regretted that a different rubber diaphragm was not employed around the subject's neck in order to transmit to the spirometer all the respiratory movements and thus enable more accurate measurement of the absolute difference in respiratory volume during mental repose and mental effort.

Since the absolute value of this probably systematic error in the ventilation measurements is unknown and difficult to determine, we have recorded in our tables the *apparent* ventilation as measured on the kymograph tracings, rather than trying to make any correction for fluctuations in the helmet diaphragm, to obtain the absolute ventilation. This correction, in our judgment, would be a plus correction that would apply equally to all the values on any one day, but the fact that such a correction has not been made does not play any great role, since our study is concerned with the *differences* in volume of ventilation in the mental effort and the rest periods. Moreover, these curves are of value in showing with relative accuracy whether there were any alterations in the speed and the depth of respiration with the change from mental repose to mental effort.

HEART RATE

The method commonly employed in the Nutrition Laboratory of determining the heart rate, namely, by attaching a Bowles stethoscope to the chest with a long tube leading to ear pieces used by the operator back of the subject, is satisfactory when rapid transitions in heart rate are not expected. In these experiments during mental effort it was desired, if possible, to obtain a continuous graphic record of the heart rate. This could be done with an electrocardiogram, but this requires the use of a string galvanometer and an elaborate equipment. Fortunately about the time of our experiments, our attention was called to the ingenious cardiotachometer of Dr. Ernst P. Boas of the Montefiore Hospital in New York City.[1] We purchased one of these

[1] Boas, E. P., Arch. Intern. Med., 1928, **41**, p. 403; Boas, E. P., and E. F. Goldschmidt, *The Heart Rate*, Baltimore, 1932.

instruments and employed it in our research. In the use of this apparatus, two simple metallic contacts were attached to the subject's chest with surgeon's plaster, commonly resting on bits of soft cotton soaked with green soap. From these contacts there were leads to another room, and there the action current of the heart was amplified by radio amplification to such a degree that it actuated an electro-magnet which wrote on a rotating drum the major impulses of the heart and also the time marks. The tape record furnished with the cardiotachometer was not satisfactory for our long-continued use of the apparatus. Consequently the Nutrition Laboratory's physicist, V. Coropatchinsky, arranged a Blix-Sandstrom kymograph with a spirally moving drum so that the records for two or three hours could be made on a single drum. This apparatus proved extraordinarily successful and can be highly recommended.

With subject A the heart rate was recorded for the most part with a stethoscope and a long tube leading to the ear pieces. Only in the last few periods of the last experiment with him was the heart rate counted by the cardiotachometer. With the other subjects, this ingenious instrument was invariably used.

RECORD OF MUSCULAR ACTIVITY

It seemed necessary, at least at the inception of our studies, to insist that the subject maintain the same degree of muscular repose in the periods of mental effort as in the repose periods. Consequently a tube pneumograph was wrapped about the abdomen, whether the subject was sitting or lying. Our subjects were extraordinarily quiet in all the experimental periods. Indeed, in our judgment there were no periods in which the muscular activity was of sufficient moment to be taken into consideration in the interpretation of the results.

ROUTINE OF AN EXPERIMENT

The subject came to the laboratory about 8.30 a. m., without breakfast, having eaten only a moderately light meal the night before. After removing the outside wraps and emptying the bladder, he usually lay upon a couch with the head in a comfortable position. In a few instances he sat in a comfortable armchair with every precaution taken to secure his complete comfort. During the preliminary rest period of half an hour, data were recorded with regard to the evening meal, time of retiring, mouth temperature, and the like. Meanwhile the electrodes were adjusted over the heart, the pneumograph was attached, the helmet was placed over the subject's head, with care to have a tight closure around the neck, and the ventilation of the apparatus immediately began. During the actual progress of each experimental period, while the apparatus was in operation, a weight was placed for a few minutes upon the spirometer bell to assure absence of leaks. Usually the subject wore the helmet without removing it throughout the entire forenoon, 2 or 3 hours, so comfortable was its adjustment. Every care was taken to eliminate, in so far as possible, all extraneous sounds in the room.

The experimental periods were each about 15 minutes long. Valves in the absorber system made it possible to deflect the air current from one set of

carbon-dioxide absorbers to the other, and thus obtain the continuous absorption of the carbon-dioxide exhaled by the subject. The metabolism was measured, first, during several consecutive periods of mental repose or of "attention," or of mental repose followed by "attention." There were then a number of periods of mental effort. The metabolism measurements during mental effort were in all instances, except with subjects IV and V, preceded by a period of about 5 or 10 minutes during which the subject did mental arithmetic, but no measurements of the respiratory exchange were made. Finally the metabolism was measured again during repose or attention. Under each particular experimental condition there were usually three or four consecutive 15-minute periods. Occasionally a second series of periods during mental effort was carried out, followed again by periods of attention or repose.

RESULTS OF EXPERIMENTS[1]

In the presentation of results, we have followed the chronological order of the experiments, as this order represents the development of our experimental method with slight changes in technique. Subject A was the first to be studied and subject VI the second, although according to the numerical numbering apparently the last. The importance of noting whether there were any rhythmic fluctuations or transitions in metabolism in the various states of mental repose, attention, and mental effort makes it desirable to present the results for the individual periods in the case of each subject. This has been done in tables 1 to 7, inclusive.

With all the subjects there were some experiments in which the oxygen consumption was recorded first by the open-circuit and then by the closed-circuit apparatus. Such changes could be made within a minute or less without disturbing the adjustment of the helmet, and hence it was possible to compare the results obtained from period to period with the two types of respiration apparatus. The invariably uniform agreement in the results obtained by these two methods makes it unnecessary to publish both sets of data or to distinguish between them in the tabular presentation of results. This comparison further confirmed us in our belief in the accuracy of our techniques.

Tables 1 to 7, which show at a glance the details of the physiological measurements with each subject, demand certain comments frequently anticipatory of the more general discussion. Consideration of these tables will be limited, however, to such comments. Obviously the general conclusion from the entire research must depend, in the final analysis, upon the picture presented by the subjects as a whole, which is shown in the average values recorded in tables 8 to 12. In all these tables the values for the carbon-dioxide elimination, the oxygen consumption, and the apparent ventilation of the lungs have been reduced to standard conditions of temperature and pressure.

EXPERIMENTS WITH SUBJECT A

Subject A, who was well trained for all types of respiration experiments, including the use of the helmet, was sitting in the first experiment (table 1) and in periods 1 to 9 with his mind as nearly as possible at rest or in a state of mental vacuity. Nevertheless there was a tendency for both the oxygen consumption and the carbon-dioxide exhalation to decrease as the morning passed. The initial, relatively high oxygen values are fully in line with the slightly higher heart rate at the start. When the effort of attention was introduced into the experiment, there was no appreciable effect upon either of the gaseous factors and consequently the respiratory quotient remained unchanged. Since no mental problems were given to the subject on this day, the data contribute information only regarding the metabolic level throughout the forenoon and the effect, if any, of attention. Although the average oxygen consumption during the periods of mental repose was 227 c.c. and

[1] The results of this research have already been reported briefly by Benedict, F. G., and C. G. Benedict, Proc. Nat. Acad. Sci., 1930, 16, p. 438.

during attention 221 c.c., if one rules out the first three period values, which are admittedly high, the average during repose becomes essentially the same as that during attention. The same is true of the carbon-dioxide output. In other words, there is no indication that the metabolism was stimulated by the alertness demanded in the attention periods. This fact is especially striking with subject A, who of all our subjects probably approximated most nearly the state of mental vacuity during the periods of mental repose. On the other hand, during attention the details of the experiment demanded alertness with a certain amount of discrimination.

The experiments on February 19 and 20 reproduced the picture noted on February 18. These three experiments together are convincing that at least with this subject the metabolism remained essentially constant throughout the forenoon, especially after the first two or three periods, and that the factor of attention was without effect upon the metabolism.

Since we planned to make most of our observations with the subjects in the lying position, the last two experiments with subject A were made while he was lying. In each case, however, the first series of attention periods was followed by periods of mental effort, these in turn being followed by one or more attention periods. On February 25 the metabolism during the mental repose and the subsequent attention periods showed precisely the same picture as noted in the three preceding experiments. In the two mental effort periods the average oxygen consumption was 4 per cent above the average noted in the preceding attention periods, but was essentially the same as the average in the repose periods. In the fourteenth period, when the subject was at attention, the carbon-dioxide exhalation returned to the initial level, the oxygen consumption was somewhat higher than in the two mental effort periods, and the respiratory quotient returned from 0.85 to 0.80. The evident irritability or chagrin of the subject in being unable to solve the simple problems given to him may have accounted for the increased metabolism in the mental effort periods.

In the last experiment with subject A, on February 27, the gaseous metabolism increased when the attention periods began. The metabolism during the repose periods, however, was notably lower than in the preceding experiment of February 25, although in both instances the subject was lying. The heart rate was unfortunately not recorded in all the periods of these experiments, and the protocols suggest no reason for the lower metabolism during repose on February 27. The fact, however, that the metabolism during the first series of attention periods on February 27 was essentially the same as that during attention on the four preceding days (although on three of these days the subject was sitting) is strong evidence that in all probability during the first four periods on February 27 subject A was drowsy. Hence it is particularly fortunate that on this day there were four attention periods that can be used as a baseline for comparison with the metabolism during the subsequent superimposed mental effort. In the two periods of mental effort there was a still further increase in the carbon-dioxide excretion, a slight increase in the oxygen consumption and an increase in the respiratory quotient. The heart rate, which was determined for the first time with the cardiotachometer in these periods, averaged 65 beats per minute. In the four subsequent attention periods, the metabolism was not much different

TABLE 1—*Subject A, man, professional artist's model*
(Sitting, February 18, 19 and 20; values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate[1]
1930		c.c.	c.c.		
Feb. 18					
1	Repose	187	234	0.80	64
2	"	185	234	.79	67
3	"	180	228	.79	66
4	"	182	218	.83	59
5	"	178	....	....	62
6	"	178	231	.77	58
7	"	178	225	.79	60
8	"	181	229	.79	63
9	"	178	214	.83	58
Average		181	227	.79	62
10	Attention	178	228	.78	....
11	"	173	219	.79	....
12	"	174	217	.80	....
Average		175	221	.79	....
Feb. 19					
1	Repose	187	224	.84	66
2	"	178	216	.82	64
3	"	183	226	.81	64
4	"	190	232	.82	65
5	"	183	207	.88	57
6	"	174	215	.81	52
7	"	179	211	.85	....
8	"	179	219	.82	....
Average		182	219	.83	61
9	Attention	177	221	.80	....
10	"	182	220	.83	....
11	"	179	225	.80	....
12	"	183	219	.84	....
Average		180	221	.82	....
Feb. 20					
1	Repose	186	225	.82	61
2	"	189	227	.83	61
3	"	181	221	.82	63
4	"	181	225	.80	59
5	"	182	235	.77	....
6	"	182	....	....	60
7	"	181	223	.81	60
8	"	174	209	.83	....
Average		182	224	.81	61
9	Attention	181	229	.79	....
10	"	178	227	.78	....
11	"	185	231	.80	....
Average		181	229	.79	....

[1] Determined with the stethoscope on February 18, 19 and 20, and by the cardiotachometer on February 27.

TABLE 1—*Subject A, man, professional artist's model*—Continued
(Lying, February 25 and 27; values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate[1]
1930		c.c.	c.c.		
Feb. 25					
1	Repose	188	232	0.81	....
2	"	187	231	.81	....
3	"	185	230	.80	....
4	"	184	225	.82	....
5	"	187	228	.82	....
6	"	180	220	.82	....
7	"	179	215	.83	....
8	"	182	231	.79	....
Average		184	227	.81	....
9	Attention	181	222	.82	....
10	"	174	220	.79	....
11	"	179	216	.83	....
Average		178	219	.81	....
12	Multiplication	197	226	.87	....
13	"	190	230	.83	....
Average		194	228	.85	....
14	Attention	186	233	.80	....
Feb. 27					
1	Repose	174	212	.82	....
2	"	172	205	.84	....
3	"	173	210	.82	....
4	"	174	213	.82	....
Average		173	210	.83	....
5	Attention	183	222	.82	....
6	"	185	226	.82	....
7	"	188	222	.85	....
8	"	....	226	....	....
Average		185	224	.83	....
9	Multiplication	200	227	.88	66
10	"	196	230	.85	64
Average		198	229	.87	65
11	Attention	196	227	.86	64
12	"	191	231	.83	....
13	"	192	228	.84	....
14	"	185	227	.82	....
Average		191	228	.84	64

[1] Determined with the stethoscope on February 18, 19 and 20, and by the cardiotachometer on February 27.

from what it had been during the mental effort, and the heart rate was practically unchanged.

In general these experiments with subject A show in four cases out of five practically no change in the metabolism between the repose and the attention periods. The experiment of February 27, on the contrary, shows a definite increase in metabolism during attention, probably accounted for by the drowsiness of the subject during the preceding repose periods. In the two instances when mental arithmetic was performed, there was a perceptible increase in both respiratory gases.

Although subject A was an ideal subject for metabolism measurements in general, he had a distinctly irritating cough throughout this entire series of observations, which resulted in several explosive respiratory efforts in many of the periods, a cough that would have dislodged a mouthpiece had he been wearing one. The experiments are worth recording, however, since they show what results can be secured with the helmet respiration apparatus even under these adverse circumstances. As already emphasized, subject A was by no means a suitable subject for mental effort experiments, although highly cooperative. His lack of experience in mathematical calculations makes these experiments of importance chiefly as orientation measurements to note whether the fact that the subject was disturbed by his inability to solve the problems with the expediency hoped for would superimpose upon the effect of the real mental effort the effects of the factors of irritation, anxiety and chagrin. Realizing that in the case of this subject the mental effort was complicated by these other factors due to his inexperience in this type of intellectual activity, we were quite prepared to find that his metabolism was definitely influenced by the mental effort. In the final analysis of our results on mental effort the data for this subject are not included.

EXPERIMENTS WITH SUBJECT VI

Since subject VI had had no experience with metabolism measurements, she was given some preliminary training on March 1. She was not in the post-absorptive condition on this day, and no effort was made to secure quantitative measurements either with or without mental effort. In all the other experiments she had been 12 hours without food. She was still menstruating regularly, although not on any of the days when her metabolism was measured. Although she had had no previous experience with metabolism experiments, she adapted herself readily and proved to be an ideal, non-temperamental subject.

On March 3 the cardiotachometer was employed, but the procedure for continuous registration of the heart rate had not been satisfactorily developed. Five records of the pulse rate taken at approximately 10-minute intervals during the first three periods on this day showed an average rate of 64 beats per minute. The respiratory exchange (see table 2) was extraordinarily uniform in the first three periods of mental repose, increased insignificantly in the following periods of attention, and increased definitely during mental effort. In the attention periods following the mental effort there was a continual decrease in both respiratory gases. The respiratory quotients fluctuated considerably, probably in large part because of the changes in the carbon-dioxide output. The respiration rate increased slightly with atten-

TABLE 2—*Subject VI, woman, professional accountant*
(Lying, March 3 and 4; values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
March 3							
1	Repose	165	202	0.82	......	10	4.7
2	"	164	203	.81	......	10	4.7
3	"	164	204	.80	......	11	4.8
Average		164	203	.81	......	10	4.7
4	Attention	165	207	.80	......	12	4.6
5	"	167	211	.79	......	11	4.7
6	"	170	206	.83	......	12	5.2
Average		167	208	.81	......	12	4.8
7	Multiplication	177	224	.79	......	13	5.7
8	"	170	217	.78	......	12	5.3
9	"	171	225	.76	......	12	5.5
Average		173	222	.78	......	12	5.5
10	Attention	178	207	.86	......	13	5.3
11	"	158	193	.82	......	11	4.7
12	"	149	197	.76	......	11	4.3
13	"	142	181	.78	......	11	3.9
14	"	153	....	....	......	11	4.3
Average		156	195	.81	......	11	4.5
March 4							
1	Repose	151	195	.77	......	12	4.8
2	"	157	190	.83	......	12	5.2
3	"	131	191	.69	63	10	3.9
4	"	139	181	.77	63	10	4.0
5	"	142	187	.76	64	10	4.1
Average		144	189	.76	63	11	4.4
6	Attention	150	175	.86	63	11	4.3
7	"	152	198	.77	74	9	4.4
Average		151	187	.82	69	10	4.4
8	Multiplication	165	209	.79	80	12	5.7
9	"	166	221	.75	79	11	5.4
10	"	163	230	.71	78	12	5.3
Average		165	220	.75	79	12	5.5
11	Attention	146	....	....	66	12	4.4
12	"	148	181	.82	66	11	4.4
13	"	146	180	.81	63	12	4.2
Average		147	181	.82	65	12	4.3

TABLE 2—*Subject VI, woman, professional accountant*—Continued
(Lying, March 5, 6 and 7; values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
March 5							
1	Repose	142	185	0.77	60	9	4.2
2	"	134	189	.72	63	10	3.9
3	"	134	184	.73	61	9	3.7
4	"	140	186	.75	63	11	3.8
Average		138	186	.74	62	10	3.9
5	Attention	148	192	.77	64	11	3.9
6	"	145	....	....	66	13	3.8
7	"	144	186	.77	66	13	3.8
8	"	136	173	.79	62	11	3.6
9	"	143	176	.81	63	11	3.7
Average		143	182	.79	64	12	3.8
10	Multiplication	151	198	.76	74	11	5.2
11	"	152	186	.82	74	11	5.3
12	"	150	185	.81	74	11	5.0
Average		151	190	.80	74	11	5.2
March 6							
1	Attention	138	173	.80	64	10	3.6
2	"	137	174	.79	61	10	3.6
3	"	141	176	.80	62	10	3.7
4	"	141	180	.78	......	11	4.0
Average		139	176	.79	62	10	3.7
5	Multiplication	159	206	.77	71	11	4.8
6	"	156	199	.78	70	11	4.8
7	"	157	202	.78	71	10	4.8
8	"	160	204	.78	70	12	4.7
Average		158	203	.78	71	11	4.8
9	Attention	148	173	.86	61	11	3.8
10	"	142	175	.81	61	12	4.0
11	"	145	176	.82	64	11	4.0
Average		145	175	.83	62	11	3.9
12	Repose	139	179	.78	60	11	3.8
13	"	138	179	.77	64	11	3.8
Average		139	179	.78	62	11	3.8
March 7							
1	Attention	141	182	.77	58	11	4.3
2	"	144	183	.79	57	11	4.0
3	"	139	181	.77	59	11	4.0
4	"	146	183	.80	......	10	4.1
Average		143	182	.78	58	11	4.1
5	Multiplication	155	191	.81	......	11	5.2
6	"	156	196	.80	68	11	5.1
7	"	152	191	.80	68	12	5.3
8	"	149	189	.79	64	10	5.2

TABLE 2—*Subject VI, woman, professional accountant*—Continued
(Lying, March 7; sitting, March 17 and 18; values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930 March 7 *Continued*		c.c.	c.c.				liters
9	Attention	146	182	0.80	58	10	4.5
10	"	144	184	.78	63	11	4.9
11	"	145	190	.76	59	11	4.6
Average		145	185	.78	60	11	4.7
12	Repose	145	182	.80	66	9	4.6
13	"	147	184	.80	63	10	4.7
Average		146	183	.80	65	10	4.7
March 17							
1	Attention	153	....	....	63	12	....
2	"	155	....	....	62	11	....
3	"	157	....	....	65	11	....
4	"	160	....	....	66	12	....
Average		156	....	....	64	12	....
5	Arithmetic problems	156	....	....	67	12	....
6	"	154	....	....	65	11	....
7	"	154	....	....	66	11	....
8	"	146	....	....	64	11	....
Average		153	....	....	65	11	....
9	Attention	152	....	....	64	11	....
10	"	151	....	....	64	10	....
11	"	154	....	....	65	11	....
Average		152	....	....	64	11	....
March 18							
1	Attention	145	184	.79	62	12	4.2
2	"	150	184	.82	62	11	4.3
3	"	147	188	.78	62	10	4.1
4	"	146	180	.81	63	10	4.0
Average		147	184	.80	62	11	4.2
5	Addition	157	191	.82	66	11	4.8
6	"	150	....	....	63	10	4.5
7	"	149	....	....	64	10	4.7
8	"	148	185	.80	63	10	4.6
9	"	149	188	.79	65	10	4.4
Average		151	188	.80	64	10	4.6
10	Attention	140	183	.77	61	12	3.9
11	"	147	181	.81	62	11	4.1
12	"	149	178	.84	64	11	4.0
13	"	151	185	.82	65	11	4.0
Average		147	182	.81	63	11	4.0

tion, increased no further with mental effort, and decreased only insignificantly in the subsequent attention periods. The apparent total ventilation of the lungs per minute remained practically unchanged in the rest and attention periods, but increased noticeably during mental effort and decreased to the initial level in the periods following the intellectual activity. The subject proved to be unusually keen in solving the problems, adapted herself easily to the entire experimental routine, and cooperated intelligently.

On March 4 both the respiratory gases were lower during repose than on the preceding day, although there is considerable irregularity in the results. During the first two attention periods the carbon-dioxide output increased, but the oxygen consumption underwent no change, on the average, from that noted in the preceding rest periods, although the two attention periods do not agree well. Both factors increased during mental effort and decreased in the subsequent attention periods. There was no significant alteration in the respiration rate throughout the entire day, and the results agree with those on March 3. The heart rate increased continually until the attention periods following mental effort, when it decreased. The apparent total ventilation of the lungs increased with mental effort, as on the day before.

On March 5 there were increases in both respiratory gases, in the heart rate, and in the ventilation rate during mental effort. During the attention periods the carbon-dioxide output increased somewhat over the basal level and the oxygen consumption decreased slightly, although the period values are very irregular. This irregularity is reflected in the respiratory quotients. Indeed, the quotients in all three experiments, March 3, 4 and 5, were very uncertain. Subject VI was unusually drowsy on March 5, which may account for the irregularity in the oxygen consumption. Another explanation may be the fact that it was difficult to make the rubber collar around the neck tight. The hair at the nape of the neck, which with women frequently presents difficulty, persisted in getting under the rubber. However, by covering the neck opening of the rubber collar with a glycerine preparation, we soon made the closure tight so that in periods 8 to 12 we were certain of the oxygen measurements.

On March 6 and on all succeeding days, the experiments began immediately with measurements during attention, since it seemed evident that there was little difference between the metabolism in complete mental repose and that with attention. In the attention periods on March 6, the usual interchange of colored lights was not used as a stimulus, but the subject was asked to respond to an electric buzzer which was sounded at about the same frequency as the rate at which the problems in multiplication were to be given. As in the three preceding experiments, the mental effort resulted in increases in the oxygen consumption, the carbon-dioxide output, the heart rate, and the ventilation rate, but there was no change in the respiration rate. During the periods of attention and mental repose following the mental effort, the respiratory exchange and the ventilation rate decreased to the initial levels before mental effort, but the respiratory quotient increased somewhat at first.

On March 7 the average oxygen consumption in the preliminary attention periods was slightly greater than on the day preceding, but the heart rate was somewhat lower. The mental effort caused increases in all the measured

factors except the respiration rate. In the periods of attention and repose following the mental effort, the respiratory exchange and the ventilation rate returned to essentially the initial level and were much the same under both attention and repose. The heart rate, however, increased during the mental repose at the end of the series. The respiratory quotient and the respiration rate were practically unaltered throughout the day.

Although subject VI adapted herself rapidly to the technique and proved to be an ideal subject for respiration experiments, the picture of the oxygen consumption per minute in the series of lying experiments shows unquestionably a decrease in metabolism from day to day. Thus, on March 3 during the periods of repose and attention preceding mental effort, the average oxygen consumption was 206 c.c. On March 4 it decreased to 188 c.c., on March 5 it was 184 c.c., on March 6 it was 176 c.c., and on March 7 it was 182 c.c. The decrease from 206 c.c. on the first day to essentially 180 c.c. on the last two days suggests that at the start the subject was under a certain stimulus (unaccompanied by visible signs of tension or anxiety) and that as the experiments continued there was a real internal adjustment to the new situation. As has been frequently emphasized in this report, however, our study was from start to finish a differential one, for we were comparing the metabolism during periods of repose with that during periods of mental effort on the same day. Consequently, although the basal level of metabolism may not have been precisely the same on all the different experimental days, there is every reason to believe that on any one day the superimposed effect of mental effort would be entirely unclouded by these differences.

On March 17 the mental problems given were not those of multiplication but simple arithmetic problems, such as those used by Chlopin and taken from one of the standard arithmetic books in the Boston schools. This necessitated that the subject should be comfortably supported in a sitting position and should have free vision so that she could easily read the problems, which had been typed on cards and which were placed one at a time in front of her. As each problem was solved, the subject pressed the telegraph key and another card was placed before her. Since the subject was sitting and it was realized that the electrodes attached to her in this position would be heavy and pull on the skin, they were not plastered to the skin as well as they should have been. Hence, although a record of the heart rate was secured in each period, these records were not determined as accurately as in the other experiments. The adjustment of the helmet to the subject in the sitting position caused some difficulty and required considerable time at the start of the experiment. It was finally concluded that the rubber diaphragm had been used too long, and it was therefore replaced with a new one at the end of the experiment. For this reason we have discarded all the oxygen values, the respiratory quotients, and the ventilation records in this experiment and have reported only the carbon-dioxide values, which were determined by weight. The degree of tightness of the rubber diaphragm about the neck would be without significance in these measurements by weight. The carbon-dioxide output decreased slightly with mental effort and in the subsequent attention periods remained practically unchanged. The intermittent observations of the heart rate showed practically no change throughout the day. The respiration rate, as usual, remained constant.

It is unfortunate that the type of mental problem given was coincidental with our dissatisfaction with the closure of the rubber diaphragm and the resultant disturbance in the oxygen measurements. However, we believe that the closure about the subject's neck was not sufficiently unsatisfactory to vitiate completely the value of the experiment, and we conclude on the basis of the carbon-dioxide measurements alone that undoubtedly this type of mental arithmetic had less effect upon the metabolism of this subject than did the problems in multiplication given in the earlier experiments. If the metabolic effect is to be taken as an index of the mental effort, it can be argued that the mental effort was likewise less in this type of problem than in the multiplication problems. The independent subjective impression of subject VI agrees fully with this hypothesis.

On March 18 the subject was again sitting. A new rubber diaphragm was employed, and we have every reason to believe that the measurements of both respiratory gases were satisfactory throughout the day, with the exception of the oxygen values in periods 6 and 7. The mental effort on this day consisted in problems in addition, such as those employed by Miles[1] in studying the psychological effects of undernutrition. The advantage of the helmet in experiments of this type can hardly be over-emphasized. It permits clear vision for the subject, the mouth and the nose are unhampered by any breathing appliances, and the subject is free to carry out the mental operations. With many individuals there are normally lip movements when additions and multiplications are being made. These lip movements are prevented when a mouthpiece is held in the mouth. In the first four attention periods on March 18 there was a striking uniformity in the gaseous metabolism and during the mental effort there were slight increases. The heart rate increased only 2 beats on the average. The respiration rate was unaltered and there was a slight, although probably insignificant increase in the apparent total ventilation. In the following four attention periods there were small decreases in the oxygen and carbon-dioxide values, but the respiratory quotient remained essentially constant. This experiment of March 18 and (although complicated by the uncertainty regarding the tightness of closure of the diaphragm about the neck) the experiment of March 17 confirm us in our belief that the solution of mental arithmetic problems or additions does not require as intense mental effort as does the multiplication of pairs of 2-digit figures.

EXPERIMENTS WITH SUBJECT I

Subject I was a university-trained man who had specialized in English, history and government, but not in mathematics. In all instances the subject was lying and the mental effort consisted in multiplication. Although on March 10 subject I had his first experience with metabolism measurements, the oxygen consumption on this day was singularly regular (see table 3). In the initial attention periods both respiratory gases decreased somewhat after the first two periods, but the respiratory quotient remained constant at 0.81, on the average. During mental effort there was a slight, probably insignificant increase in the gaseous exchange. The oxygen consumption

[1] Benedict, F. G., Miles, W. R., Roth, P., and H. M. Smith, Carnegie Inst. Wash. Pub. No. 280, 1919, fig. 19, p. 143.

TABLE 3—*Subject I, man, college graduate—lying*
(Values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
March 10							
1	Attention	183	222	0.82	65	15	4.8
2	"	178	227	.78	72	15	5.1
3	"	178	217	.82	......	15	5.1
4	"	177	218	.81	69	15	4.8
5	"	176	217	.81	73	15	4.8
Average		178	220	.81	70	15	4.9
6	Multiplication	183	221	.83	73	16	5.1
7	"	183	228	.80	72	16	5.1
8	"	180	222	.81	71	17	5.0
9	"	178	223	.80	65	17	5.1
Average		181	224	.81	70	17	5.1
10	Attention	172	223	.77	......	14	4.9
11	"	180	225	.80	......	15	5.2
12	"	183	235	.78	67	15	5.3
13	"	186	238	.78	68	16	5.3
Average		180	230	.78	68	15	5.2
14	Repose	195	245	.80	66	15	5.3
15	"	193	243	.79	......	15	5.7
Average		194	244	.80	66	15	5.5
March 11							
1	Attention	177	224	.79	71	15	5.3
2	"	166	213	.78	66	14	4.8
3	"	162	209	.78	63	14	4.7
4	"	163	210	.78	63	14	4.8
5	"	174	213	.82	66	14	5.1
Average		168	214	.79	66	14	4.9
6	Multiplication	179	224	.80	71	17	5.6
7	"	178	233	.76	72	16	5.8
8	"	179	234	.76	71	15	5.9
9	"	175	221	.79	67	16	5.4
Average		178	228	.78	70	16	5.7
10	Attention	175	231	.76	67	15	5.5
11	"	185	235	.79	66	15	5.7
12	"	177	218	.81	65	15	5.4
13	"	183	240	.76	66	16	5.6
Average		180	231	.78	66	15	5.6

TABLE 3—*Subject I, man, college graduate—lying*—Continued

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
March 12							
1	Attention	179	212	0.84	65	13	4.2
2	"	163	199	.82	60	14	3.9
3	"	161	202	.80	58	14	3.7
4	"	181	206	.88	59	14	5.0
5	"	167	197	.85	60	14	4.1
Average		170	203	.84	60	14	4.2
6	Multiplication	176	199	.88	63	15	4.7
7	"	175	201	.87	59	15	4.5
8	"	170	207	.82	58	15	5.0
9	"	173	205	.84	60	15	4.5
Average		174	203	.85	60	15	4.7
10	Attention	163	203	.80	59	15	4.3
11	"	165	202	.82	......	15	4.5
12	"	174	208	.84	......	15	4.5
13	"	169	215	.79	......	15	4.4
Average		168	207	.81	59	15	4.4
14	Repose	176	225	.78	......	14	4.6
15	"	176	211	.83	......	14	4.5
Average		176	218	.81	......	14	4.6
March 13							
1	Attention	165	207	.80	60	14	5.0
2	"	167	208	.80	59	14	5.0
3	"	177	206	.86	67	14	5.1
4	"	167	200	.84	......	15	5.1
Average		169	205	.83	62	14	5.1
5	Multiplication	179	207	.86	69	16	5.4
6	"	176	206	.86	68	15	5.5
7	"	178	209	.85	68	16	5.7
8	"	175	209	.84	66	16	5.4
Average		177	208	.85	68	16	5.5
9	Attention	165	204	.81	62	15	5.0
10	"	170	207	.82	62	15	5.0
11	"	171	211	.81	62	15	5.3
12	"	166	209	.79	62	15	5.0
Average		168	208	.81	62	15	5.1
13	Repose	171	214	.80	65	15	5.3
14	"	180	222	.81	65	15	5.0
Average		176	218	.81	65	15	5.2

TABLE 3—*Subject I, man, college graduate—lying*—Continued

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
March 14							
1	Attention	185	212	0.87	71	14	5.5
2	"	177	210	.84	68	15	5.4
3	"	159	201	.79	63	14	4.9
4	"	163	201	.81	61	15	5.1
5	"	164	197	.83	62	15	5.3
6	"	169	198	.85	62	15	5.5
Average		170	203	.83	69	15	5.3
7	Multiplication	169	193	.88	65	16	5.8
8	"	171	202	.85	65	16	5.7
9	"	171	200	.86	65	15	5.6
10	"	170	202	.84	62	15	5.5
Average		170	199	.86	64	16	5.7
11	Attention	158	199	.79	65	14	5.1
12	"	162	191	.85	59	14	5.4
13	"	167	....	....	60	15	5.4
14	"	170	205	.83	59	14	5.5
Average		164	198	.82	61	14	5.4

increased from the time of the cessation of mental effort until the end of the series of measurements, and the carbon-dioxide excretion increased during the two final periods of repose. The heart rate (although recorded somewhat intermittently and with a certain number of errors, as the cardiotachometer was not working any too well) fluctuated considerably but averaged 70 both during the preliminary attention periods and during mental effort. During attention and repose following mental effort, it was somewhat lower. The respiration rate underwent a slight, insignificant increase during mental effort. The apparent ventilation of the lungs increased regularly throughout the morning. This experiment of March 10 as a whole showed no appreciable increase in metabolism as a result of mental effort, but in the attention periods following mental effort the metabolism was higher and in the periods when the subject was in repose it was still higher. When such results are obtained in ordinary metabolism work, one is inclined to consider that the prolonged morning session has been irksome to the subject and that there may have been a desire to urinate. If this were true in the case of subject I on March 10, the increased metabolism would be explained by an internal cause aside from the mental effort. The subject did not report any discomfort from retention of urine in the bladder, however. One could argue therefore that in this case there was possibly an after-effect of mental effort. This should be borne in mind in the subsequent discussion.

We can fairly assume that the first experimental day was an orientation day for subject I and that on March 11 he was sufficiently trained to under-

stand completely the experimental procedure and therefore would perhaps be less affected by any changes in technique. In the preliminary attention periods the oxygen consumption after the first period remained practically constant and was, on the average, slightly less than in the preliminary attention periods on the day before. The carbon-dioxide output was noticeably less than under similar conditions on the day before. This accounts for the difference in the initial respiratory quotients on March 10 and 11. The heart rate was likewise somewhat less than on the day before, the respiration rate was essentially the same, and the apparent ventilation of the lungs per minute exactly the same. During mental effort all the measured factors except the respiratory quotient increased. In the final attention periods the oxygen, carbon-dioxide, and ventilation values were at the same levels as during mental effort, the respiratory quotient was unchanged, and the heart rate was slightly lower. This second experiment with subject I gives the same picture of a sustained effect of mental effort continuing into the attention periods following the intellectual activity.

On March 12 during the preliminary attention periods the oxygen consumption remained practically constant after the first period and was lower than on March 11. The initial carbon-dioxide elimination was almost the same as in the preliminary attention periods on March 11, the heart rate was lower, the respiration rate the same, and the apparent ventilation of the lungs slightly lower than the corresponding values on the day before. During mental effort the oxygen consumption and the heart rate remained unchanged, the respiration rate increased only insignificantly, and the other factors increased slightly. In the attention periods following mental effort, as on the two preceding days, the oxygen consumption was at a somewhat higher level but the carbon-dioxide output decreased. During the last two periods of repose both of these factors increased. The respiration rate remained unchanged after mental effort and the apparent ventilation of the lungs decreased somewhat.

On March 13 the oxygen consumption during the initial periods of attention averaged much the same as under similar conditions on the preceding day. During mental effort the oxygen consumption increased only slightly but the carbon-dioxide output increased to a greater extent. During attention following mental effort the oxygen consumption remained unchanged, but the carbon-dioxide output decreased. In the last two periods, when the subject was supposed to be relaxed and at ease, there were increases in both of these factors. Indeed, the oxygen consumption was at its highest level in these last two periods. The heart rate increased during mental effort, decreased during the succeeding attention periods, and increased again during the final periods at ease. The respiration rate, the apparent ventilation of the lungs, and the respiratory quotients increased slightly during mental activity and decreased in the subsequent attention and repose periods.

The average basal metabolic level on March 14 was the same as on March 12 and March 13. During mental effort there was no change in the carbon-dioxide exhalation, but there was a slight decrease in the oxygen consumption, this resulting in a small increase in the respiratory quotient. During the subsequent attention periods the oxygen consumption, contrary to increasing as in some of the preceding experiments, remained at the same level as during

mental effort, but the carbon-dioxide output decreased slightly. The heart rate decreased throughout the experiment. The respiration rate underwent practically no change, being only slightly increased during mental effort. There was the usual slight increase in the apparent ventilation of the lungs during the intellectual activity.

From these five experiments it is evident that with subject I the observations were too prolonged for the experiments to be considered ideal. Undoubtedly the measurements were affected by fatigue and internal restlessness, although externally the subject appeared quiet and tranquil. The kymograph tracings of the subject's body movements, as determined by means of the pneumograph attached to the bed springs, indicated no marked activity, and the usual indications of discomfort (restlessness and desire to urinate) were not present. It is clear, however, that this subject, in common with many individuals, could not adapt himself to a long-continued series of observations. Fortunately the fact that the mental effort periods with subject I did not come at the end but in the middle of the series helps somewhat in the interpretation of the results. Thus in the differential method, even if there was a gradual, continued increase in metabolism because of fatigue, which would lower the percentage effect of the superimposed factor of mental effort, the measurements as arranged in the experiments with subject I should still show the increase caused by mental effort, if there is such an increase. On the other hand, if the periods of mental effort came at the end of a long series of measurements and the metabolism was higher in these periods, this would not necessarily prove that mental effort had increased the metabolism, since there is a tendency with many individuals in long-continued experiments to have a fairly regular increase in metabolism as time goes on. In studying the effect of any superimposed factor therefore, one should avoid the element of fatigue caused by too long an experimental session.

EXPERIMENTS WITH SUBJECT II

Subject II had been a chemist on the Nutrition Laboratory staff for some time, had been a subject for respiration experiments on numerous occasions, and was thoroughly familiar with metabolism technique. He received training in the particular technique employed in these mental effort experiments on the afternoon of March 18. On March 19 (see table 4) all the factors measured except the respiratory quotient increased during mental effort. On the resumption of the attention periods there was an immediate decrease in the carbon-dioxide output, but the oxygen consumption continued at the high level for the first period (period 9) and thereafter decreased. The average carbon-dioxide and oxygen values in the final attention periods were at essentially the initial levels prior to the mental activity. The heart rate returned to the initial level, the respiration rate returned to almost the initial level, and the apparent total ventilation of the lungs was slightly lower than at the start. The respiratory quotient underwent wholly insignificant changes with the exception of the first attention period after mental effort, when a low value of 0.75 was noted.

The reaction of subject II to the multiplication problems (2-digit figures) given in the experiment of March 19 was rapid, and it was evident that he

TABLE 4—*Subject II, man, college graduate, chemist—lying*
(Values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
March 19							
1	Attention	184	221	0.83	60	15	6.4
2	"	173	211	.82	59	14	6.1
3	"	170	211	.81	59	16	6.2
4	"	163	209	.78	56	16	5.5
Average		173	213	.81	59	15	6.1
5	Multiplication	197	228	.86	70	20	7.5
6	"	179	231	.77	67	20	6.9
7	"	177	226	.78	69	19	6.7
8	"	179	223	.80	68	20	6.8
Average		183	227	.80	69	20	7.0
9	Attention	171	228	.75	62	16	5.9
10	"	167	215	.78	59	16	5.5
11	"	166	214	.77	57	16	5.4
12	"	176	216	.81	59	17	6.1
13	"	173	214	.81	59	17	5.9
Average		171	217	.78	59	16	5.8
March 20							
1	Attention	188	211	.89	59	16	5.0
2	"	171	203	.84	54	15	4.2
3	"	169	206	.82	51	15	4.1
4	"	178	204	.87	55	15	4.5
Average		177	206	.86	55	15	4.5
5	Multiplication	194	221	.88	67	18	5.5
6	"	184	212	.87	65	19	5.2
7	"	183	215	.85	64	19	5.2
Average		187	216	.87	65	19	5.3
8	Attention	170	202	.84	59	14	4.3
9	"	161	202	.80	56	14	3.9
10	"	164	203	.81	56	15	4.2
Average		165	202	.82	57	14	4.1
11	Multiplication	187	210	.89	64	19	5.3
12	"	186	215	.87	65	19	5.2
13	"	181	212	.85	65	19	5.0
Average		185	212	.87	65	19	5.2
14	Attention	176	219	.80	60	15	4.5
15	"	174	209	.83	60	16	4.5
Average		175	214	.82	60	16	4.5

TABLE 4—*Subject II, man, college graduate, chemist—lying*—Continued

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
March 21							
1	Attention	169	218	0.78	62	15	5.6
2	"	170	213	.80	61	14	5.4
3	"	172	209	.82	64	15	5.5
Average		170	213	.80	62	15	5.5
4	Multiplication	179	215	.83	65	18	6.4
5	"	177	214	.83	65	18	6.4
6	"	177	215	.82	64	18	6.1
Average		178	215	.83	65	18	6.3
7	Attention	174	209	.83	61	15	5.7
8	"	162	205	.79	58	14	4.9
9	"	181	216	.84	58	14	5.9
Average		172	210	.82	59	14	5.5
10	Multiplication	183	217	.84	63	17	6.4
11	"	184	224	.82	64	17	6.4
12	"	182	224	.81	64	18	6.5
Average		183	222	.82	64	17	6.4
13	Attention	166	215	.77	57	14	5.6
14	"	164	212	.77	57	13	5.0
Average		165	213	.77	57	14	5.3
March 22							
1	Attention	170	218	.78	59	14	5.3
2	"	169	205	.82	56	14	5.3
3	"	175	209	.84	58	15	5.5
Average		171	211	.81	58	14	5.4
4	Multiplication	181	214	.85	61	17	6.1
5	"	184	214	.86	62	18	6.6
6	"	181	214	.85	62	18	6.3
Average		182	214	.85	62	18	6.3
7	Attention	167	212	.79	56	14	5.2
8	"	164	204	.80	56	13	5.2
9	"	177	208	.85	57	14	5.7
Average		169	208	.81	56	14	5.4
10	Multiplication	185	217	.85	60	17	6.0
11	"	182	216	.84	60	17	6.0
12	"	180	214	.84	60	17	5.9
Average		182	216	.84	60	17	6.0
13	Attention	165	210	.79	55	14	5.4
14	"	170	206	.83	58	13	5.1
Average		168	208	.81	57	14	5.3

could solve the problems more readily than could subjects A, VI, and I. Indeed, the reaction was so rapid that we decided to increase one of the 2-digit figures to a 3-digit figure by the addition, at the left, of the number 3 in each case. Thus, a problem that had formerly been 68 times 17 became 368 times 17. As was to be expected, the subject afterward reported that he found these problems much more difficult and that it was a great effort to keep the figures of the answer in mind. Subsequent discussion brought out the fact that he had employed several "short cuts." Thus, 99 times 4 became 400 minus 4. There is no question, however, but that the mental effort of this subject was conscientiously sustained throughout the entire time when the problems were being given. Since this subject seemed so unusually adept at mental arithmetic, we attempted to check the accuracy of his mental operations. On the afternoon of March 19, after the metabolism measurements had been completed and subject II had had his lunch, the problems were again given to him, both in their original form and with the additional digit, and his answers were recorded. These answers were subsequently compared with the known, accurate solutions of the problems. Since we were seeking, in the first place, for sustained mental effort and only secondarily and quite incidentally for accuracy, we were interested to note that in the multiplication of the 2-digit numbers the subject was accurate to a fairly high degree. When the third digit was added, the accuracy was considerably lessened, but was sufficient to indicate that the subject was making a serious effort to complete the problems as presented to him. This confirms us again in the belief that the multiplication of 2- and 3-digit figures calls for sustained, intense mental effort and that subject II exhibited particular facility in this type of mental problem.

In the experiment of March 20 there were two series of measurements during mental effort, preceded and followed by observations during attention. The arithmetic problems consisted of multiplying 3-digit numbers by 2-digit numbers. In the preliminary attention periods the gaseous exchange was almost the same as on March 19. The respiratory quotient was a little higher, the heart rate somewhat lower, the respiration rate the same, and the apparent total ventilation of the lungs considerably lower than on March 19. As we have already pointed out, however (see page 37), one can compare the results for the apparent ventilation only in different periods on the same day, but not from day to day, owing to the unavoidable fluctuation in the degree of distention of the rubber diaphragm around the subject's neck, which depends somewhat upon the adjustment of the helmet. In the first series of measurements during mental effort on March 20 there were increases in all the factors measured except the respiratory quotient, which remained unaltered. In the following three periods of attention, periods 8 to 10, the oxygen consumption decreased to slightly below the initial level and the carbon-dioxide output fell to considerably below the initial level. The result was a somewhat lower respiratory quotient. The heart rate decreased to almost the initial level, the respiration rate returned to the initial level, and the apparent total ventilation decreased to somewhat below the rate at the start. In the second series of measurements during mental effort, all the factors increased to the same or essentially the same levels as noted in the first series of mental effort periods. In the last two

periods, during attention, the oxygen consumption did not decrease, the carbon-dioxide output did, and therefore there was a marked change in the respiratory quotient. The heart rate decreased somewhat, although it did not become so low as during periods 1 to 4. The respiration rate and the apparent total ventilation per minute returned to the levels noted in the initial attention periods. In the slightly higher oxygen consumption during the last series of attention periods, we have a suggestion of the fact that not infrequently a long-continued series of observations may result in an actually increased metabolism even before definite external evidences of discomfort or restlessness appear. The subject was very quiet and there was no indication that he was not comfortable. Any experimental plan, however, involving many consecutive metabolism measurements should intersperse periods of mental effort with comparison periods during repose, at not too great intervals from each other.

The two experiments on March 21 and 22 show much the same picture as was noted on March 20, namely, increases in the measured factors of the same order of magnitude in both series of measurements during mental effort and decreases to essentially the initial basal levels during the two series of attention periods following the two mental effort series. In general, in the first two experiments with subject II, there was a definite increase in metabolism as a result of the stimulus of mental effort, but in the last two experiments the reaction was somewhat less.

EXPERIMENTS WITH SUBJECT III

At the time when this research on mental effort was in progress, there was at the Nutrition Laboratory a visiting fellow of the Rockefeller Foundation, Professor J. Petřík, of the Department of Physiology of the University of Brno, Czechoslovakia. Professor Petřík kindly offered to serve as subject (subject III) in two experiments. He had already familiarized himself with the various forms of respiration apparatus in the Nutrition Laboratory, had assisted in some of the experiments made on subject II, and hence was acquainted with the technique.

On March 24 (see table 5) the oxygen consumption and the carbon-dioxide exhalation were extraordinarily regular during the first four attention periods and increased during mental effort. In the succeeding attention periods both respiratory gases returned to their initial levels before the mental effort. The respiratory quotient remained unchanged, on the average, throughout the experiment. The usual increases in heart rate, respiration rate, and apparent ventilation of the lungs noted with the other subjects during mental effort were likewise observed with subject III.

In the experiment on March 25 two series of measurements were made during mental effort. The first three periods of attention again showed a remarkably uniform oxygen consumption. In the first series of observations during mental effort there were increases in both respiratory gases and a slight increase in the respiratory quotient. In the two succeeding periods during repose (periods 7 and 8), both factors were lowered to approximately the same levels as prior to the mental effort. With the resumption of mental effort in periods 9 and 10, both factors again increased to essentially the same levels as during the first series with mental effort. The heart rate increased

during the first series of mental effort periods, decreased during the succeeding attention periods, and rose again, but only slightly, in the second series during mental effort. The respiration rate underwent no particular change. The apparent total ventilation rate increased somewhat during the first series of mental effort periods, but increased to a higher level in the second series.

In these experiments subject III found it necessary to translate the problems first from English into Czech (his native tongue) and then compute the

TABLE 5—*Subject III, man, university professor—lying*
(Values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
March 24							
1	Attention	181	235	0.77	61	14	5.6
2	"	178	232	.77	60	14	5.7
3	"	180	231	.78	58	14	5.5
4	"	180	231	.78	57	15	5.7
Average		180	232	.78	59	14	5.6
5	Multiplication	187	242	.77	64	17	6.4
6	"	186	239	.78	64	17	6.5
7	"	193	243	.79	64	17	6.2
Average		189	241	.78	64	17	6.4
8	Attention	177	230	.77	57	15	5.6
9	"	180	233	.77	56	16	5.9
10	"	186	233	.80	57	15	5.5
11	"	180	240	.75	56	15	5.7
Average		181	234	.77	57	15	5.7
March 25							
1	Attention	178	225	.79	59	15	4.5
2	"	174	225	.77	59	15	4.6
3	"	169	225	.75	56	15	4.6
Average		174	225	.77	58	15	4.6
4	Multiplication	184	229	.80	61	15	4.9
5	"	185	232	.80	62	15	5.0
6	"	183	235	.78	62	12	4.6
Average		184	232	.79	62	14	4.8
7	Repose	170	230	.74	51	14	4.3
8	"	171	224	.76	49	14	4.4
Average		171	227	.75	50	14	4.4
9	Multiplication	184	230	.80	53	15	5.0
10	"	180	235	.77	53	15	4.9
Average		182	233	.79	53	15	5.0

results. Needless to say, with this subject the mental effort was intense throughout the entire period when problems were given, the effort being divided between the actual mathematical calculations and the translation from one language into another. The subject reported that he had a distinct impression that the accuracy of his calculations decreased greatly as the experimental periods progressed and that it became more and more difficult for him to solve the problems correctly. Judging from the number of problems undertaken per period, we infer that he became fatigued, although in each series there were not more than three 15-minute periods of multiplication problems. If the number of problems solved per 15 minutes is any measure of fatigue, there was a clear indication of a slowing of accomplishment in the last two of the three successive mental effort periods on both experimental days. This man's subjective impressions were that he had been through a period of intense, sustained mental effort on both days.

EXPERIMENTS WITH SUBJECT IV

During the first series of mental effort periods with subject IV on March 27 (see table 6), the oxygen consumption continually increased, the carbon-dioxide output increased slightly, and hence there was no noticeable change in the respiratory quotient. In one of the two periods of mental repose (period 6) following the mental effort, there was an error in the oxygen determination. The oxygen consumption in period 7 was noticeably less than that during the preceding periods of mental effort and was somewhat less than that during periods 1 and 2 when the subject was at rest. The carbon-dioxide output decreased during the repose periods following the first series of multiplication problems. In periods 8, 9 and 10 the subject again was given the arithmetic problems and both respiratory gases increased. There were then two periods of rest (periods 11 and 12) when the oxygen consumption remained, on the average, at the same level as during the mental effort, but the carbon-dioxide output decreased. In the last two periods, 13 and 14, during attention the subject was uncomfortable because of the desire to urinate. This discomfort was undoubtedly reflected in the higher oxygen consumption, but not appreciably in the carbon-dioxide excretion. The heart rate increased in both series of mental effort periods. The heart rate alone would not indicate that the subject had been uncomfortable at the end of the experiment, although the personal impression of the subject was quite the contrary. The respiration rate underwent practically no change throughout the entire experiment. The ventilation rate increased slightly during mental effort.

On April 1, the measurements on subject IV in periods 1 and 2 were made during mental repose and those in period 3 during attention. Both respiratory gases were lower in the one attention period than in the two rest periods. The measurements obtained in these three periods have been averaged, however, to represent the basal values for subject IV on this day. In the three periods of mental effort, neither the oxygen consumption nor the carbon-dioxide excretion underwent any change. In the final periods of rest, there was a decrease in both factors. The respiratory quotient underwent only slight changes and decreased in the last two rest periods.

TABLE 6—*Subject IV, man, college graduate, physiologist—lying*
(Values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
March 27							
1	Repose	197	233	0.85	55	14	6.8
2	"	207	244	.85	55	15	7.1
Average		202	239	.85	55	15	7.0
3	Multiplication	210	242	.87	58	14	7.7
4	"	205	248	.83	58	14	7.4
5	"	209	255	.82	60	15	7.2
Average		208	248	.84	59	14	7.4
6	Repose	193	....	....	55	14	6.9
7	"	191	231	.83	54	15	7.5
Average		192	231	.83	55	15	7.2
8	Multiplication	200	242	.83	56	15	7.5
9	"	206	243	.85	58	15	7.5
10	"	199	253	.79	58	15	7.3
Average		202	246	.82	57	15	7.4
11	Repose	193	238	.81	54	15	7.3
12	"	201	253	.79	57	14	7.4
Average		197	246	.80	56	15	7.4
13	Attention	200	255	.78	55	14	7.2
14	"	195	258	.76	54	14	7.3
Average		198	257	.77	55	14	7.3
April 1							
1	Repose	211	247	.86	55	15	7.7
2	"	203	248	.82	55	15	7.5
3	Attention	189	237	.80	53	15	7.1
Average		201	244	.83	54	15	7.4
4	Multiplication	197	239	.82	56	16	8.1
5	"	204	248	.82	57	16	8.0
6	"	204	245	.83	58	16	7.5
Average		202	244	.82	57	16	7.9
7	Repose	188	237	.79	55	15	6.5
8	"	197	243	.81	56	14	6.6
Average		193	240	.80	56	15	6.6

Subject IV was distinctly conscious of attempting to visualize the problems that were given to him. Indeed, he found it necessary at times to close the eyes while solving the problems, to avoid the slight distraction of the eyes

wandering from one part of the room to another. Jacobson,[1] in studying the technique of progressive relaxation, has noted that during the mental process there is actually an ocular tension. He believes that one can quiet the mind by extreme, progressive relaxation of the muscles of the eyes and the speech apparatus.

EXPERIMENT WITH SUBJECT V

Thanks to the kindness of Dr. T. M. Carpenter (subject V), we were able to carry out a series of observations on him. Dr. Carpenter has served on many occasions over a long period as a subject for experimental studies in the Nutrition Laboratory, and is thoroughly familiar with all the details of the technique. The experiment on April 3 with subject V (see table 7) differed from most of the experiments with the other subjects in that he was sitting rather than lying. Subsequently he was convinced that this was a mistake and that it would have been preferable if he had been lying throughout the series of measurements, although he also felt that he might have been uncomfortable lying so long in one position. During mental effort the gaseous metabolism increased, but there was no appreciable change in the respiratory quotient. In the succeeding periods of rest (periods 7 and 8),

TABLE 7—*Subject V, man, college graduate, physiologist—sitting*
(Values per minute)

Date and period	Mental state	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate	Apparent ventilation of lungs (reduced)
1930		c.c.	c.c.				liters
April 3							
1	Repose	151	172	0.88	73	16	5.6
2	"	147	168	.87	71	17	6.0
3	"	150	169	.89	71	16	5.8
Average		149	170	.88	72	16	5.8
4	Multiplication	168	185	.91	76	14	7.1
5	"	160	180	.89	77	14	6.6
6	"	159	181	.88	77	14	6.6
Average		162	182	.89	77	14	6.8
7	Repose	150	176	.85	74	16	5.8
8	"	148	172	.86	73	17	5.9
Average		149	174	.86	74	17	5.9
9	Multiplication	164	188	.87	77	15	6.6
10	"	160	182	.88	78	15	6.5
11	"	160	183	.88	77	15	6.5
Average		161	184	.88	77	15	6.5
12	Repose	152	177	.86	73	18	6.2

[1] Jacobson, E., Journ. Nervous and Mental Diseases, 1924, **60**, p. 568; *ibid.*, Amer. Journ. Physiol., 1930, **95**, p. 694.

both respiratory gases returned to essentially their initial levels. Indeed, the respiratory quotient was slightly lower than at the start. In the second series of observations during mental effort the carbon-dioxide excretion and the oxygen consumption were at the same levels as in the first series of periods with mental effort and noticeably above the values found in the rest periods. In the single rest period at the end of the experiment, both factors decreased. The heart rate increased during both mental effort series and decreased during rest. The respiration rate of subject V was somewhat different from that of the other subjects, in that during both series of measurements with mental effort it was somewhat lower than during the rest periods. On the other hand, the apparent total ventilation of the lungs showed the characteristic increase during mental effort and decreased to approximately the original level during rest.

GENERAL DISCUSSION

PHYSIOLOGICAL NORMALITY OF SUBJECTS

It has been the custom of a number of investigators to utilize either adolescent or wholly untrained individuals in studying the influence of mental effort upon metabolism. In our judgment, in observations on as subtle a factor as this, one should be certain that the subjects employed are capable of sustained, intense mental effort. The normality of the subjects used for this type of experiment should therefore be passed upon from two different standpoints, (1) as to whether they are physiologically normal and (2) as to whether they are psychologically alert and of normal mental caliber. Only one of our subjects (A) can be classified as not particularly qualified for sustained mental effort such as was demanded in our study. This subject's long experience in several thousand metabolism measurements seemed to make him an ideal subject, so far as training is concerned, and he was apparently normal physiologically, but the results obtained with him must be omitted from any general considerations owing to his insufficient ability in arithmetical performance. All but one of our other subjects (I to VI) were university graduates and all were mentally alert. With regard to physiological normality we did not require that our subjects should be given a physical examination by a physician. They were all in active service and apparently in good health, facts that would indicate physiological normality. A second index of their normality is obtained in a consideration of their basal metabolism.

TABLE 8—*Deviation of measured basal metabolism from Harris-Benedict predictions*

Subject	Sex	Age	Body weight (without clothes)	Height	Oxygen absorbed per minute	Heat production per 24 hours		
						Measured	Predicted	Deviation from predicted
		years	kg.	cm.	c.c.	cal.	cal.	p.ct.
A	M	47	68.0	166	223	1549	1515	+ 2.2
I	M	25	57.1	176	210	1459	1564	− 6.7
II	M	26	66.5	188	211	1466	1746	−16.0
III	M	36	65.2	172	230	1598	1580	+ 1.1
IV	M	59	79.6	183	240	1668	1678	− 0.6
V	M	52	50.0	165	[1]	[1]	[1]	[1]
VI	F	44	55.1	155	186	1292	1263	+ 2.3

[1] Subject measured only while sitting; hence comparison with predicted metabolism is not justified.

Deviation of measured from predicted metabolism—The ages, weights and heights of our subjects are recorded in table 8. In addition, the average metabolism of our subjects when post-absorptive and in the lying position, based upon all the periods of complete mental repose and attention, has been referred to the metabolism as predicted by the Harris-Benedict stand-

ards[1] for men and women of similar ages, weights and heights. The "measured" heat production has been calculated from the average oxygen consumption, on the assumption that each liter of oxygen has a caloric value of 4.825 calories. Since subject V was measured only in the sitting position, the comparison with the prediction has not been made in his case. With all except subject II, the measured metabolism closely approximated the predicted metabolism. The one aberrant deviation of the measured from the predicted metabolism is noted with subject II, namely, −16.0 per cent. Comparison with the Aub and Du Bois prediction standard in the case of this subject gives a deviation of −19 per cent. The relationship between the height and the weight of this subject is challenging. Although subject II was extremely tall and appeared unusually thin, in his several years of service at the Nutrition Laboratory he had been well, had been rarely absent for any illness, was at the time of his experiments presumably in good health, and at the present day (May 1933) is still in apparently perfect health. Certainly in the case of our other five subjects for whom the comparison can be made, the basal metabolism was fully in conformity with the predicted values based upon measurements on a large number of normals and, judged by this standard alone, our subjects were physiologically normal.

Further evidence with regard to the physiological normality of these subjects, including especially subject II, is given in the values in table 9 dealing with the respiratory quotient, the heart rate, and the respiration rate. The values in this table are averages of the basal measurements made from day to day during those periods without mental effort. In making these averages we have included in most instances all the period values when the subjects were in mental repose and at attention, regardless of whether these periods preceded or followed the mental effort. This procedure is justified by the fact (already pointed out in the discussion of tables 1 to 7 and further discussed on page 70) that the metabolism of our subjects was essentially the same during attention as during mental repose and that there was no after-effect of mental effort. Since with subject I the element of fatigue undoubtedly explains the higher values noted on some days in the periods of rest and attention near the end of the experiment, we have based the averages in his case (see footnote 2, table 9) on those periods that seem most representative of the metabolism during rest and attention unaffected by fatigue. The averages for subject IV on March 27 do not include periods when there was discomfort from desire to urinate. In addition to the averages recorded in table 9 for the observations made with the subjects while lying, we have included the averages for those rest and attention periods carried out while the subjects (A, V and VI) were sitting, so that we might study the influence of difference in body position upon the metabolism (see page 69).

The average values for the respiratory quotient, which indicates the character of the material burned in the body, are all well within normal limits. The aberrant quotients in basal periods so frequently reported in the literature without seemingly attracting any special attention are here conspicuous by their absence. Further examination of the details in tables 1 to 7, where the respiratory quotients during mental effort are reported,

[1] Harris, J. A., and F. G. Benedict, Carnegie Inst. Wash. Pub. No. 279, 1919, tables I to IV, pp. 253–266.

TABLE 9—*Metabolism of subjects (post-absorptive) from day to day in mental repose and during attention*
(Average values per minute[1])

Subject, position, and date	Carbon dioxide eliminated	Oxygen absorbed	Respiratory quotient	Heart rate	Respiration rate
1930	c.c.	c.c.			
A (lying)					
Feb. 25	183	225	0.81	....	....
Feb. 27	183	221	.83	64	....
Avg.	183	223	.82	64	....
A (sitting)					
Feb. 18	179	225	.80	62	....
Feb. 19	181	220	.83	61	....
Feb. 20	182	225	.81	61	....
Avg.	181	223	.81	61	....
VI (lying)					
March 3	161	201	.81	....	11
March 4	146	186	.79	65	11
March 5	141	184	.76	63	11
March 6	141	176	.80	62	11
March 7	144	183	.79	60	10
Avg.	147	186	.79	63	11
VI (sitting)					
March 17	155	....	....	64	11
March 18	147	183	.81	63	11
I (lying)[2]					
March 10	178	220	.81	70	15
March 11	168	214	.79	66	14
March 12	169	205	.83	60	14
March 13	169	207	.82	62	15
March 14	167	202	.83	63	15
Avg.	170	210	.82	64	15
II (lying)					
March 19	171	215	.80	59	16
March 20	172	207	.83	57	15
March 21	170	212	.80	60	14
March 22	170	209	.81	57	14
Avg.	171	211	.81	58	15
III (lying)					
March 24	180	233	.77	58	15
March 25	172	226	.76	55	15
Avg.	176	230	.77	57	15
IV (lying)					
March 27[3]	196	237	.84	55	15
April 1	198	242	.82	55	15
Avg.	197	240	.83	55	15
V (sitting)					
April 3	150	172	.87	73	17

[1] Each average value, except for subject I, represents all observations during repose and attention, both before and after mental effort.
[2] Averages on March 10 and 11 represent only periods 1 to 5; March 12, periods 1 to 5 and 10 to 13; March 13, periods 1 to 4 and 9 to 12; March 14, all periods at rest or attention.
[3] Averages on March 27 represent only periods 1, 2, 6, 7, and 11; periods 12, 13, and 14 not included because of discomfort of subject.

will also show that rarely, if ever, were any aberrant quotients found. Thus we have in the normality of the respiratory quotients another indication that our subjects were physiologically normal and, what is more, that they were psychologically normal. When a person is unduly apprehensive, the respiration rate is disturbed and the respiratory quotient is invariably altered. Here in these basal periods of mental repose and attention, the respiration rate was normal with all the subjects (although subject VI had a low rate of 11) and the respiratory quotients were normal.

Just what is the average normal heart rate is always debatable. In its observations on numerous individuals, the Nutrition Laboratory has noted occasionally some extraordinarily low heart rates. Thus some students on reduced rations frequently had heart rates of 40[1] and male Maya in Yucatan were found to have pronouncedly low rates.[2] Subjects I and VI had higher heart rates during the basal measurements than subjects II, III and IV, but certainly none of them had subnormal rates.

DAY-TO-DAY VARIATION IN BASAL METABOLISM

As has been pointed out in our survey of the literature, wide variations in the oxygen consumption on different days have been uncritically accepted by some investigators, undoubtedly on the ground that they are using a differential method and comparing the metabolism during mental effort on a given day with the metabolism during repose on the same day. Although this procedure seems logical, we maintain that those individuals that show great variability in their basal or standard metabolism are not suitable subjects with whom to study so subtle a superimposed factor as mental effort. One has but to turn to the protocols of Rosenblum to see a splendid illustration of uniformity in metabolism with his different subjects. Our own series of *basal* metabolism measurements recorded in table 9 shows that with any given subject the variability from day to day in the average values for the measured factors was very small. It is not surprising that with subjects I and VI, who were unaccustomed to these measurements,[3] the metabolism was higher on the first day than on subsequent days. But in general, except for the first days with these two subjects, the oxygen and similarly the carbon-dioxide values from day to day with the same subject agree well. This uniformity in the metabolic processes indicates satisfactory adjustment of the bodily and mental states to the experimental conditions.

The question is frequently asked as to how uniform the metabolism of an individual remains from day to day. In innumerable physiological studies in which the same subject is used for many experiments one finds in the literature all too frequently wholly impossible differences in the metabolism as measured on different days. This we believe is an indication of faulty

[1] Benedict, F. G., Miles, W. R., Roth, P., and H. M. Smith, Carnegie Inst. Wash. Pub. No. 280, 1919, pp. 384 et seq.

[2] Williams, G. D., and F. G. Benedict, Amer. Journ. Physiol., 1928, **85**, p. 634; Shattuck, G. C., and F. G. Benedict, Amer. Journ. Physiol., 1931, **96**, p. 518; Steggerda, M., and F. G. Benedict, Amer. Journ. Physiol., 1932, **100**, p. 274.

[3] The method employed by Rounds, Schubert, and Poffenberger (Journ. Gen. Psychol., 1932, **7**, p. 65) of having the subject go through a 30-day period of preliminary training prior to the mental effort tests is highly to be commended. Unfortunately, however, even under these ideal conditions their subject was not post-absorptive and hence day-to-day comparisons are thereby complicated.

technique, inadvertent eating on the part of the subject, or of some other unrecorded factor. The basal data in table 9 show that with the exception of the two first days with subjects I and VI the agreement from day to day in the various factors measured is extraordinarily close. This leads to the belief that under normal conditions the basal metabolism of the same individual on several days not too far apart is essentially constant. This is far from asserting that the practice indulged in by certain investigators is permissible, of measuring the basal metabolism on one day, the metabolism as affected by some superimposed factor on a following day, and referring the latter measurement to the prior determination of the basal metabolism. Even when the increased metabolism of severe muscular work is under study, a constant basal metabolism may not be assumed. This has been the practice in a number of laboratories, including those interested in animal experiments, and has led to numerous false conclusions. We believe that this regularity in the resting metabolism of our subjects from day to day justifies us in adversely criticising the results of those earlier investigators who found such tremendous variability from day to day in the metabolism of the same subject. Indeed, we are convinced that their subjects, if not their techniques, were not suitable for the study of the effect of such a subtle factor as mental effort.

INFLUENCE OF BODY POSITION UPON BASAL METABOLISM

The data with two of our subjects (see table 9) enable us to compare the metabolism as affected by the sitting and the lying positions. Ideally this comparison should be based upon measurements made on the subject in the two positions on the same day. This was not the case in our experiments, and the comparison therefore is contrary to the idea expressed above. However, in view of the remarkable uniformity in the basal metabolism of our subjects from day to day, we believe that it is not wholly illogical to compare the metabolism of the subject sitting on one day with the metabolism of the subject lying on another day. Since in this particular series of experiments every effort was made to have the sitting position unusually comfortable, the subject being well supported with cushions to avoid strain, the metabolism was essentially the same with subjects A and VI whether they were sitting or lying. This finding is in conformity with the inference drawn from experiments made many years ago at the Nutrition Laboratory, that if the subject is sitting so well supported by pillows that the pulse rate is no greater than when the subject is lying, the metabolism is the same in both positions.[1] Kaplan[2] has also pointed out that body position (lying and sitting) has no influence on the level of the metabolism. In our judgment this fact has particular bearing on hospital procedure in metabolism measurements. A strong movement is in force to introduce metabolism measurements as a feature of the physical examination of a patient upon entrance into the hospital. Psychologically a patient sitting up is much less apt to be disturbed by such measurements than is one lying down. It is believed that it would be of advantage psychologically to permit the patient to sit in a wheel chair or in a semi-reclining position and that there would be no

[1] Emmes, L. E., and J. A. Riche, Amer. Journ. Physiol., 1911, 27, p. 406.
[2] Kaplan, P. M., Arbeitsphysiologie, 1933, 6, p. 413.

significant alteration in the metabolism measured under these conditions. Admittedly the data obtained on our two subjects throw only a little light on this problem, but they are in line with our own belief based upon many experiments at the Nutrition Laboratory.

MENTAL EFFORT AND METABOLISM

BASELINE FOR COMPARISON WITH METABOLISM DURING MENTAL EFFORT

Early in our experimental program it became evident that the transition from mental vacuity or repose to attention was without significant effect upon any of the measurements. Hence in some of the later experiments we decided to discontinue the observations during complete repose and to measure the "baseline" metabolism only during the so-called "attention" periods. At first sight this would seem to be in contradistinction to the thesis laid down in an earlier part of this paper, namely, that one should superimpose the effect of the mental effort upon the metabolism at its lowest level or irreducible minimum in order that the increment, if there were any, might be more readily measurable. Only when we were satisfied, however, that there was no difference in the metabolism between complete repose and attention, did we feel justified in foregoing the measurements during repose. Because of the undenied difficulty of subjects in keeping awake during periods of repose, that is, without any stimuli whatsoever, we believed that there was a greater liability of error entering into the rest periods. When in complete repose, the subject is apt to become drowsy and under such conditions the metabolism will decrease. On the other hand, the factor of discrimination called for in the attention periods insured a much more uniform metabolic state prior to and following the mental stimuli. As pointed out in the discussion of tables 1 to 7, no after-effect of mental effort was noted in the periods of measurement following the mental effort. As a baseline for comparison with the average metabolism of our subjects during mental effort, therefore, we have considered it proper to average the results, in the case of each measured factor, of all the period values during repose and attention on all experimental days, regardless of whether these periods preceded or followed the mental effort.

RESPIRATORY AND CIRCULATORY ACTIVITY

Heart rate—In table 10 a comparison is made of the average values for the heart rate, the respiration rate, and the apparent total ventilation of the lungs per minute during rest and attention and during mental effort. Subject A is not included in this and the following tables, because he was used only for orientation experiments and because not all these factors were measured in his case. In those experiments where two series of measurements were made during mental effort, the results of both series are included in calculating the average metabolism during the intellectual activity. With subject VI the average values in table 10 (as also in table 12) represent the results obtained both in the lying and the sitting positions. The records of the heart rate were made as objective as possible, both from the standpoint of the subject and that of the operator. In all the experiments represented by the averages in table 10 electrodes were fastened to each subject's chest

and from the electrodes there were wires leading to the cardiotachometer in another room, where the heart rate was graphically recorded on a kymograph. Hence the subjects were unaware of the counting of the heart rate. The mental effort resulted in a measurable increase in the heart rate of 2 beats on the average with subject I, 3 beats with subject IV, 4 beats with subjects III and V, and 7 beats with subjects II and VI. In general, the heart rate increased from an average of 62 to 66 beats per minute, or an increase of 6.5 per cent.[1]

TABLE 10—*Effect of mental effort on heart rate and respiratory activity*
(Average values per minute)

Subject[1]	Heart rate		Respiration rate		Apparent ventilation of lungs (liters)	
	Rest and attention	Mental effort	Rest and attention	Mental effort	Rest and attention	Mental effort
I	64	66	15	16	4.9	5.3
II	58	65	15	19	5.3	6.2
III	57	61	15	16	5.1	5.7
IV	55	58	15	16	7.1	7.7
V	73	77	17	15	5.9	6.7
VI	63	70	11	11	4.2	5.1
Average	62	66	15	16	5.4	6.1

[1] Subjects I to IV were lying in all experiments; subject V was sitting; subject VI was lying in 5 experiments and sitting in 2 experiments.

Respiration rate—With subject V the respiration rate decreased on the average during mental effort, with subject VI it remained unchanged, and with the other subjects it increased. The average respiration rate per minute of all the subjects during rest and attention was 15 and during mental effort, 16. The average increase here is probably insignificant.

Apparent ventilation of the lungs—Examination of the tracings of the excursions of the spirometer bell indicates that during mental effort the type (depth and not infrequently rate) of respiration was altered. This picture shown by the kymograph tracings is likewise reflected in the average values for the apparent ventilation of the lungs. The systematic error in these results has already been pointed out (see page 37), but the fact that these values may be 20 or 25 per cent too low does not affect the comparison here. With every one of the subjects, the mental effort resulted in an increase in the apparent ventilation of the lungs. This increase ranged from a minimum of 8 per cent with subjects I and IV to a maximum of 21 per cent with subject VI. In general, when the subjects were lying, the apparent ventilation of the lungs averaged 5.4 liters per minute during rest and attention and 6.1 liters during mental effort. The average increase was therefore 13 per cent.

[1] Gillespie (Journ. Physiol., 1923–24, 58, p. 425) also notes an increase in pulse rate during mental effort.

CARBON-DIOXIDE OUTPUT

Our carbon-dioxide measurements represent not the carbon dioxide produced, but only that exhaled or eliminated. One should hold this distinction in mind in the following considerations. In view of the altered type of respiration during mental effort as shown by the spirometer tracings and in view of the average increase of 13 per cent in the apparent ventilation of the lungs per minute, the effect of mental effort on the carbon-dioxide exhalation assumes special interest. In table 11 the results of a typical experiment are given for each of our subjects I to VI, in which the average carbon-dioxide

TABLE 11—*Effect of mental effort on carbon-dioxide exhalation*
(c. c. per minute)

Condition	Subject and date					
	I March 10	II March 19	III March 25	IV March 27	V April 3	VI March 6
Average during rest or attention periods before mental effort	178	173	174	202	149	139
During mental effort, in consecutive 15-min. periods—						
Period 1	183	197	184	210	168	159
Period 2	183	179	185	205	160	156
Period 3	180	177	183	209	159	157
Period 4	178	179	....	....	....	160

output per minute during the rest and attention periods prior to the mental effort is compared with the per minute values for the carbon-dioxide exhalation during consecutive 15-minute periods of mental activity. With all the subjects, the carbon-dioxide output increased during mental effort, the maximum increase being 15 per cent with subject VI and large increases of 13 and 14 per cent being noted with subjects V and II.

Although the measurement of the carbon-dioxide exhalation as an index of the effect of mental effort has been criticized, owing to the fact that the carbon-dioxide output is immediately affected by any changes in the mechanics of respiration, nevertheless if we are willing to accept the carbon-dioxide output as a relative measure of the metabolism, the data in table 11 are of interest in indicating the course of the carbon-dioxide output as the periods of mental effort progressed. Since each period of measurement was approximately 15 minutes long, our subjects at the end of the fourth period had been engaged in intense mental effort for one hour. In general, there was a slight decrease in the carbon-dioxide output in the latter part of the mental effort series, probably explained by the fact that the novelty of the multiplication problems had worn off. But after this slight decrease, there was no hint of a further change in the carbon-dioxide exhalation. Certainly there was no change that would suggest an increased metabolism coincidental with the mental fatigue noted at the end of the experiments by these subjects.

Neither was there a cumulative increase in the carbon-dioxide output during mental effort, for at the end of an hour of intense mental effort the amount of carbon dioxide exhaled was no greater than during the first 15 minutes. Judging from the measurement of the carbon-dioxide output alone, therefore, one could conclude that an effect upon metabolism of mental effort is definitely shown. Because of the increased apparent ventilation of the lungs during mental effort noted with all the subjects, however, one would *a priori* predict an increase in carbon-dioxide exhalation. Hence consideration of the carbon-dioxide values alone still leaves it unsettled whether or not mental effort *per se* causes an increase in metabolism.

It may be that the apparent increase in the carbon-dioxide output shown in table 11 is derived in large part from preformed carbon dioxide already existing in the blood and body fluids and not produced at the time of the mental effort. Some of this preformed carbon dioxide may be swept out of the body by increased ventilation of the lungs and does not represent an increase in the output of carbon dioxide as a specific result of mental effort. The average increment in carbon-dioxide output during all the periods of mental effort (not merely those listed in table 11) with our subjects I to VI was 9 c.c. per minute (169 c.c. per minute, on the average, during rest and 178 c.c. per minute during mental effort). This increase would amount to 135 c.c. in 15 minutes. From experiments made at the Nutrition Laboratory in which the subjects designedly over-ventilated the lungs, it was found that from 4.5 to 8 liters of carbon dioxide per 15 minutes might be blown off in excess of the amount eliminated during normal breathing. Hence even after one hour of sustained mental effort, with an increased output of 540 c.c. of carbon dioxide, it can be seen that there has been no heavy draft upon the excess preformed carbon dioxide that may exist in the body. The possibility of continuing the mental effort until all this preformed carbon dioxide is swept out could not be considered by us, owing to the fatigue experienced by our subjects. This consideration illustrates clearly the difficulty that has been encountered in many earlier investigations in which the measurement of the carbon-dioxide output alone has been used as an index of the energy transformations during mental effort. The measurement of the carbon dioxide exhaled may not alone be used for such a purpose, since the possibility for error in assuming that the amount measured is that simultaneously produced is so great. Only when the carbon-dioxide measurement is accompanied by a simultaneous determination of the apparent ventilation of the lungs or, still better, the absolute ventilation of the lungs, can one interpret the carbon-dioxide measurement intelligently. In this particular case the increased ventilation of the lungs may have accounted wholly for the increase in the carbon dioxide exhaled.

OXYGEN CONSUMPTION

Whatever may be the objection to using the carbon-dioxide measurement as an index of the total metabolism, no such criticism applies to the measurement of the oxygen consumption. The importance of accurate determinations of the oxygen consumption led us to measure this in as many different ways as possible. As pointed out in the description of our techniques, the oxygen consumption was measured with a closed-circuit apparatus, the reduction

in the volume of air resulting from the absorption of oxygen being compensated by the introduction of oxygen into the system through a gas meter. Other determinations were made with the open-circuit apparatus, when a sample of the air coming from the helmet was analyzed to note its oxygen deficit. Numerous control tests, both with burning alcohol and with fasting subjects, showed that the two methods gave identical results. Hence we feel sure of the technical soundness of our oxygen measurements. Since the more labile gaseous factor, carbon dioxide, showed on analysis no hint of a cumulative effect of the mental effort, as is seen in the four consecutive periods illustrated in table 11, it is unnecessary to give here in detail the oxygen figures, which show precisely the same absence of a cumulative effect. In table 12 are recorded the grand average values for the oxygen consumption of each of our subjects (not including subject A, with whom the observations were chiefly for orientation purposes) during rest and attention and likewise during mental effort, based upon all the different experiments made with them. Here again, as in table 9, the averages for rest and attention include all the periods of mental vacuity and attention, whether they preceded or followed the mental effort, but do not include any periods in which the element of discomfort entered. With all but subject V the results in table 12 represent averages of observations on from 2 to 7 days. With subject V the results are for one day. On each experimental day there were from 5 to 11 periods of rest and attention and from 3 to 5 consecutive periods of mental effort. Moreover, in many instances two series of mental effort periods were made on one day. Hence in no case are we dealing with isolated observations.

TABLE 12—*Effect of mental effort on oxygen consumption*

Subject	O_2 per minute (c. c.)	
	Rest and attention	Mental effort
I	210	212
II	211	219
III	230	237
IV	240	246
V	172	183
VI	186	199
Average	208	216

Examination of table 12 shows that there was in all instances an increase in the oxygen consumption, on the average, during mental effort. The lowest increase was 2 c.c. per minute, or less than 1 per cent with subject I, and the highest increase was 13 c.c. or 7 per cent with subject VI. The average oxygen consumption of all the subjects increased from 208 to 216 c.c. per minute with mental effort, or 4 per cent. These results make it clear that there is an increased oxygen consumption as a result of mental effort. That this increase is directly ascribable to the localized cerebral processes

involved in mental effort is far from shown. Precisely as the carbon-dioxide measurements can not be interpreted without some knowledge of the mechanics of ventilation, here again one must remember in interpreting this slight increase in oxygen consumption that as a result of the mental tests there was a demonstrable increase in the heart action and a considerable increase in the respiratory action, particularly as shown by the ventilation of the lungs. These increases in circulatory and respiratory activity represent muscular work, and muscular work is known to cause an increased metabolism. Consequently we believe that the increased heart action and the increased ventilation of the lungs account in large part, if not wholly, for the increase in oxygen consumption noted in these experiments and that only an insignificant fraction of the increase (the mathematical value of which can not be determined) can be ascribed to the purely mental processes. Under the circumstances we believe that the influence of mental effort *per se* upon the gaseous metabolic processes of the body is so slight that it can not be measured, even with the best metabolism technique of the present day.

In the preceding discussion of the carbon-dioxide values, it was assumed that all of the increase in the carbon dioxide exhaled was derived from preformed carbon dioxide existing in the body. From this analysis of the oxygen values, however, it seems logical to reason that since there was an average increase of 4 per cent in the oxygen consumption, undoubtedly part of the increase in the carbon-dioxide output may be ascribed to an increase in the production of carbon dioxide accompanying the increased oxygen consumption. If the carbon-dioxide production was increased by mental effort, percentagewise, the same as the oxygen consumption, that is, 4 per cent, then on the average about 7 c.c. of the total average increase of 9 c.c. noted in the carbon-dioxide output would be ascribable to the metabolic increase accompanying the incrment in oxygen consumption. There would be left only 2 c.c. to be accounted for as labile, preformed carbon dioxide. Hence the possibility of exhausting this source of preformed carbon dioxide by long-continued mental effort is very remote. In our own series, as has been shown above, the percentage increases in carbon-dioxide elimination and oxygen consumption were, on the average, almost the same. Since there was no evidence of a change in the character of the material burned as a result of increased respiratory and circulatory activity, it can be assumed that the carbon-dioxide increase was likewise attributable to the increased muscular effort in these two physiological processes. This does not lessen, however, the obligation of experimenters to observe and, in so far as possible, control the conditions of lung ventilation and thus insure that the relatively great increases in carbon-dioxide exhalation as noted by other writers are not in large part due simply to over-ventilation.

RESPIRATORY QUOTIENT

The fact that the carbon-dioxide exhalation increased more percentagewise during mental effort than the oxygen consumption leads to the supposition that the respiratory quotient, that is, the ratio between the carbon dioxide exhaled and the oxygen absorbed, is different during mental effort from what it is during repose. The respiratory quotient underwent changes from time to time during the course of these experiments, as can be seen from an

examination of tables 1 to 7. Comparison of the average quotients obtained with each subject during all the rest and attention periods and during all the periods of mental effort shows that with subjects IV and VI there was no change in the quotient during mental effort, with subject I there was an increase of 0.01, with subjects III and V an increase of 0.02, and with subject II of 0.03. There can be two interpretations of the increase, when noted. One can argue that because the respiratory quotient (which supposedly indicates the character of the material burned in the body) increased, there was a change in the type of material burned in the body and that the mental effort called for a somewhat larger combustion of carbohydrates. This argument would be in line with the present theories with regard to the exclusive combustion of carbohydrate during severe muscular work. Such a conclusion is by no means justified, however, in view of our interpretation of the increased carbon-dioxide exhalation during mental effort. As already pointed out, any disturbance in the mechanics of respiration, particularly an increased ventilation rate, will alter the exhalation but not necessarily proportionately the production of carbon dioxide. Such an increase in the carbon-dioxide output, unaccompanied by an increase in the absorption of oxygen, will result in an increase in the *apparent* respiratory quotient. Hence we believe that the changes in the apparent respiratory quotients noted in these experiments are to be interpreted solely as occasioned by changes in the carbon-dioxide exhalation and not as caused by any change in the character of the material burned in the body as a result of the mental effort. In other words, because there is a seeming increase in the respiratory quotient, it is not to be argued that mental effort is accomplished at the expense of carbohydrate combustion, since this increase may well be merely an expression of differences in the volume of air passing through the lungs or an indication of the washing out of previously formed carbon dioxide.

HEAT PRODUCTION

Since the heat production is calculated from the oxygen consumption, the picture shown by the heat values will be the same as that noted with the oxygen consumption. But as another method of expressing the metabolism, that is, in terms of heat, the calculation of the heat production is included in our discussion of the results. The heat production has been computed from the oxygen consumption during rest and attention and during mental effort by assuming an average respiratory quotient of 0.82, under which conditions the caloric value of oxygen is 4.825 calories per liter. In these calculations we have made no allowance for the change in the respiratory quotient during mental effort, on the assumption that the greater exhalation of carbon dioxide noted during the mental effort was derived not from the combustion of carbohydrates, but from the sweeping out of preformed carbon dioxide. The average heat production thus calculated amounts to 60.2 calories per hour during mental vacuity and 62.5 calories per hour during mental effort. The increase with mental effort is 2.3 calories or 4 per cent. To calculate precisely the proportion of this 4 per cent that may be ascribable to the mental activity, aside from the known increased circulatory and respiratory activities, is hardly justified. But even with the grossest possible errors in assumptions as to the value of the respiratory and circulatory activities,

the residuum of the percentage increase applicable to mental activity must ultimately be so small that, in the light of the total metabolic processes necessarily measured, that is, the pooled activities of the entire body, this residuum can hardly be said to be outside the normal limit of error.

FOREHEAD TEMPERATURE

At present it seems to us that the only practical ways of studying with man the *localized* effects of mental effort are to measure the skin temperature of the forehead and the insensible perspiration. Indeed, our observations on any localized effects were limited to these two types of measurement. It may be argued that since the skin temperature of the forehead is normally high, this suggests normally a large blood supply to the brain, and that if the temperature of the forehead further increases during mental effort, this would indicate a greater supply of blood to the brain during such a process. Furthermore, in view of the highly vascular nature of the face and forehead it may be argued that the vaporization of water vapor from the forehead (with its high skin temperature) will contribute considerably to the total insensible perspiration from the body and that during mental effort there might be a greater insensible loss from this part of the body.

At the close of some of the experiments, one or two of the subjects spoke of their clear impression that there was a considerable development of heat in the body during the mental effort, particularly about the head. As a result of these comments, observations were made on a few occasions of the temperature of the air leaving the helmet, by placing a thermometer in the outgoing air current. It was thought that if the mental effort caused any material change in the temperature of the head, there would be an increase in the temperature of the air leaving the helmet. In several such tests an increase was actually noted, but these tests were false for we found that these increases could be correlated with the small movements of the head which brought the head nearer to the exit opening of the helmet. When the head remained fixed in position, there was practically no change in the temperature of the air leaving the helmet, and it was concluded that the mental effort caused no significant increase in the flow of blood to the skin of the head.

In order not to base the conclusion solely on the measurements of the temperature of the air leaving the helmet, observations were made of the forehead temperature of subject IV on March 29, 1930, both during repose and during mental effort. The electric thermo-junction method previously described[1] was employed, and the skin temperature was measured at a point on the forehead just above the bridge of the nose (so-called "position 26"), since it had been demonstrated by earlier investigations that the temperature of the head is highest at this spot. The thermo-junction placed on the forehead was of a different type from that ordinarily employed, in that its two

[1] Benedict, F. G., Miles, W. R., and A. Johnson, Proc. Nat. Acad. Sci., 1919, **5**, p. 218; *ibid.*, Sci. Amer. Supp., 1919, **88**, p. 311; Benedict, F. G., Asher-Spiro's Ergebnisse der Physiologie, 1925, **24**, p. 594; Benedict, F. G., Coropatchinsky, V., and M. D. Finn, Journ. de Physiol. et de Pathol. gén., 1928, **26**, p. 1; *ibid.*, Leopoldina (Amerikaband), Berichte d. kaiserl. Leopoldinischen Deutsch. Akad. d. Naturforscher zu Halle, 1929, **4**, p. 129.

ends were out straight instead of being curved like a hairpin. Furthermore, the wires used were finer than usual. One junction was laid exactly on the middle of the forehead. The copper lead of this junction passed over the left temple and the constantan lead over the right temple. The wires were held on the forehead by bits of adhesive tape, and sufficient traction was put upon them so that the central junction was slightly pressed into the skin. The other junction was in an ordinary thermos bottle. The system was connected with a galvanometer, as usual.

The temperature of the room was held constant throughout the observations. The subject, after having had a light lunch, lay down on a cot and the junction was attached. He remained lying, in mental repose, until the temperature of the forehead became constant, which did not take a long time. The usual multiplication problems were then given, during which records of the forehead temperature were obtained by noting continuously the deflections of the galvanometer. There was then a rest period, to note whether the forehead temperature changed following the mental effort. The series of observations were then repeated. No significant alteration in forehead temperature was noted, although there was a slight tendency for the temperature to become lower as the experiment progressed. This small decrease is explained by the fact that the subject had been moderately exercising in walking about the building before the experiment began and that he then lay down in a cool room. Subject IV found it somewhat difficult to solve the multiplication problems lying down and thought he might accomplish more if sitting. Accordingly he was allowed to sit up in a chair, the thermo-junction was readjusted and well fastened to the skin, and further temperature measurements with and without mental effort were made for approximately 5 minutes. Again there was no significant alteration in the forehead temperature, the change, if any, being in the direction of a slight decrease.

The failure to find any increase in forehead temperature during the solving of the multiplication problems confirms the fact that the temperature of the air leaving the helmet changed only insignificantly during the mental effort periods, provided the subject's head remained at the same relative distance from the opening of the exit tube. Apparently mental effort of the sustained, severe type does not measurably alter the blood supply to the brain,[1] if the skin temperature of the forehead is accepted as an index of any such change. Hence it would appear that whatever blood supply is necessary for mental activity is already available in the normally existing liberal blood supply of the brain, and that no excess supply is needed during mental effort. This is another indication of the many factors of safety found throughout the entire anatomical arrangement of the body. It is recognized, however, that these skin temperature measurements hark back to the old days of cerebral thermometry (although the technique is somewhat more sensitive and accurate) and that the assumption that surface temperatures are indices of intensity of combustion inside the brain cavity is most seriously to be challenged.

[1] This conclusion is not in conformity with the conception of H. Renauld, 2. Cong. Internat. Hyg. Aliment., Bruxelles (Proc.) 1 (1910), Sect. 1, p. 11; *ibid.*, Rev. de l'Univ. de Brux., 1910–11, 16, p. 157.

INSENSIBLE PERSPIRATION

Some of our subjects were also of the impression that during mental effort they became very warm, not only in the face and forehead but throughout the entire body. The problem therefore arose as to whether there was a real increase in cutaneous circulation during mental effort or simply a subjective impression of warmth. With subject II, who had spoken particularly of having had this impression of increased warmth during the intellectual activity, and with subject III observations were made on April 7 and 8 of the insensible perspiration before, during and following mental effort. Each of these subjects was suspended on a 100-kg. Sauter balance,[1] and the insensible loss in weight was noted in successive periods of from 10 to 15 minutes in length. The subjects were not post-absorptive but had had lunch. When the insensible loss in complete physical and mental repose became constant per unit of time, the multiplication problems were given to the subject to solve, and further observations were made. There was finally a period of rest, with continued observations of insensible loss. These measurements showed that the mental effort did not alter the insensible perspiration in the slightest. The fact that mental effort caused little, if any, vasomotor change with subject IV was therefore confirmed by these measurements.

K. W. Kuo,[2] of the Physiological Laboratory, Manchuria Medical College, Moukden, found that mental arithmetic caused a marked sweating in the axilla and the palm. According to experiments in the Nutrition Laboratory[3] the contribution of the hand to insensible perspiration is large. Hence our inability to find changes in insensible perspiration during mental effort is in contradistinction to what one would expect from the findings of Kuo. It is a matter of considerable regret that the excellent series of articles reporting the researches from the Moukden Laboratory can only with difficulty be interpreted by us, in spite of the English abstracts accompanying the papers. Evidently no one who is interested in insensible or sensible perspiration should overlook these important articles, and yet the fact that they are published in Japanese makes it impossible, even with the unusually extended English abstracts, to understand the true meaning and all the details of these studies. Two other papers by Kuo[4] dealing with perspiration during mental stress are unfortunately not at our disposal. From the abstract journals one infers that the findings are essentially those reported in his 1930 paper. Most of Kuo's work was done at environmental temperatures outside those that prevailed during our observations, and his sweat studies were confined to certain localities of the body rather than dealing with the entire surface of the body.

Y. Kuno,[5] of the same laboratory in Moukden, emphasizes that mental arithmetic used to cause mental stress resulted in sweating on the palms and soles only and not on other parts of the body surface. Kosaka,[6] likewise of the same laboratory, drew much this same conclusion from his experiments.

[1] Benedict, F. G., and H. F. Root, Arch. Intern. Med., 1926, **38**, p. 1; Benedict, F. G., and C. G. Benedict, Biochem. Zeitschr., 1927, **186**, p. 278; Benedict, F. G., Zeitschr. f. d. ges. exp. Med., 1933. (In press.)

[2] Kuo, K. W., Journ. Oriental Medicine, 1930, **13**, p. 49.

[3] Benedict, F. G., and H. S. H. Wardlaw, Arch. Intern. Med., 1932, **49**, p. 1019.

[4] Kuo, K. W., Journ. Oriental Medicine, 1931, **14**, p. 33; *ibid.*, Journ. Oriental Medicine 1932, **16**, p. 48.

[5] Kuno, Y., Lancet, April 26, 1930 (Pt. 1), p. 912.

[6] Kosaka, T., Journ. Oriental Medicine, 1929, **10**, p. 75.

CONCLUSIONS AND SUMMARY

Our investigation on the metabolism during mental effort was made with seven subjects, six men and one woman. Of these, one who was unusually tall for his weight had a basal metabolism averaging 16 per cent below the present-day accepted standard for a man of his age, weight and height, but nevertheless appeared normal in every respect. The basal metabolism values for all the other subjects were very close to the normal standards. For this reason and because of the uniformity in the basal metabolism of each subject from day to day, we are confident we were dealing with physiologically and psychologically normal individuals, whose metabolism was not apt to undergo large and sudden fluctuations.

There will always be a discussion as to what is and what is not mental effort. We had to content ourselves with subjects who had a good educational background, who cooperated seriously in the efforts to secure both mental activity and mental repose and who could adjust themselves reasonably well to the experimental technique. It was highly desirable that the mental efforts of these various individuals should be reasonably comparable. In the earlier series by Benedict and Carpenter, students taking examinations in the university on all conceivable subjects were employed, and it is a fair question whether or not the mental effort of the student writing an examination in history, involving chiefly memory work, is comparable to that of the student solving problems in higher mathematics. It would have been ideal could we have had as subjects a number of individuals especially skilled in mathematical calculations of a higher order. Probably the mental effort of such individuals would be less contaminated with emotional coloration or irritation than that of individuals less skilled in higher mathematics. The impracticability of expecting men or women of such intellectual eminence to fit their time to a prolonged experimental program need not be discussed. Furthermore the effort of the outstanding mathematical genius in solving what to the layman would appear to be impossible problems might not be productive of any greater mental activity than that actually experienced by our subjects. Although we believe that the problem of the metabolism during mental effort has been in our series of experiments studied with a sufficient number of people of satisfactory mental caliber to lead to definite conclusions, it is not impossible that in the future some mathematical and physiological zealot may find it desirable to study the problem with subjects whose entire lives are devoted to higher mathematics, an occupation which all investigators (especially psychologists), hardly without exception, agree requires the greatest amount of mental effort. From our own experience we confidently predict that the metabolism picture in such a series of experiments will be precisely that reported in these pages.

Examination of the earlier literature indicates a strong belief that mental effort causes a considerable increase in general metabolism. Few writers have been as conservative as Grafe,[1] who in 1923 concluded that the observa-

[1] Grafe, E., *Die pathologische Physiologie des Gesamtstoff- und Kraftwechsels bei der Ernährung des Menschen*, Munich, 1923, p. 425; *ibid.*, Bethe's Handb. d. normalen u. pathologischen Physiologie, 1928, 5, p. 199.

tions published up to that time were too contradictory and too few in number to decide this question. In the light of our research it is evident that carbon-dioxide measurements alone may lead to false deductions, that many of the previous investigations were carried out during a period of adjustment and not during actual mental effort, and that in order to determine the true effect of mental effort the person used in the study should not be measured over too long a period, as otherwise the element of physical fatigue will enter, which itself will increase the metabolism.

From a consideration of the various factors measured in our investigation it is concluded that sustained, intense mental effort, consisting chiefly in the multiplication of pairs of 2-digit figures, causes an increase in heart rate, an insignificant, hardly measurable increase in respiration rate, a marked alteration in the character of the respiration, a considerable increase in the apparent total ventilation of the lungs, a small increase in the carbon-dioxide exhalation, a smaller increase (on the average, 4 per cent) in the oxygen consumption and heat production, and a slight increase in the apparent respiratory quotient. In the repose periods following mental effort all the factors measured were, except in a few instances of discomfort or fatigue, lower than during mental effort and, indeed, tended to return to the original levels prevailing before the mental effort. The results of the second mental effort series on the same experimental day duplicated for the most part those of the first. There was no indication of a summation effect or of a greater increase in the second mental effort series over that of the first. Furthermore, during the progress of the four consecutive 15-minute periods of mental effort there was no evidence of any greater effect upon the factors measured during the latter periods than during the first periods (which followed an adjustment period of about 10 minutes of mental effort).

Skin-temperature measurements on the forehead and measurements of the insensible perspiration indicated that there was no appreciable alteration in the blood supply to the skin of the head and no change in the insensible loss during mental effort.

Our results in general confirm those previously obtained by Benedict and Carpenter. We are in full agreement with Dodge and other critics, however, who maintain that in the Benedict and Carpenter series the pulse records were poorly taken and that there was too long a time between the experiments with mental effort and the control tests. The fact, however, that these observations made a quarter of a century ago led to practically the same conclusions as those derived from this present research speaks well for their general accuracy.

The increase in oxygen consumption, which may be taken as the best index of the energy transformation, is such as to suggest that the increase in heat production as a result of intense mental effort of this type can hardly be of the order of more than 3 or 4 per cent. These small increases in oxygen consumption and heat production are in large part to be accounted for by the increased muscular activity accompanying the increased ventilation of the lungs and the increased heart rate. Hence, making a most conservatively small allowance for the effect of increased circulatory and respiratory activities in this small metabolic increase, we conclude that mental effort *per se* is without significant influence upon the energy metabolism.

In view of the sense of extreme, almost over-powering fatigue in both mind and body following sustained mental effort, it is surprising that mental effort has such an insignificant effect upon the general level of vital activity. This pronounced sense of mental and physical fatigue following mental effort, noted by so many mental workers, can hardly be explained by the slightly increased physical activity of the heart and respiratory muscles. Our study gives us little, if any, direct evidence for a satisfactory explanation of this feeling of extreme fatigue.

As Holmes[1] frequently emphasizes in his excellent review, too little is known of the chemistry and morphology of the brain and nothing is known of the brain metabolism during intense mental activity. The extreme unlikelihood that the brain cells participating in mental activity can locally produce anywhere near the 4 per cent increase in heat production noted in our mental effort experiments is emphasized in a personal communication from Professor Arnold Durig of Vienna. He argues that the total mass of the active brain cells involved in mental activity can hardly weigh more than 7 grams, or one one-hundredth of 1 per cent of the entire body. Consequently if these cells, in case they are functioning, are considered to be the localized cause for the 4 per cent increase in heat production, they must have a metabolic activity 400 times greater than that of the average cell metabolism of the entire body. Durig carefully points out that the metabolism *for* mental effort is different from the metabolism *due to* mental effort.

The 4 per cent increase in heat production during mental effort may be compared with the increases in metabolism accompanying various light muscular activities. Most muscular activities call for a considerable increment in heat production. In one of the large respiration chambers at the Nutrition Laboratory, metabolism measurements during a number of light household activities have been made.[2] These showed that reading aloud increased the metabolism of a group of young women 3 per cent; standing quietly, 9 per cent; hemming, 13 per cent; dusting and sweeping, on the average, 140 per cent. The 4 per cent increase in heat production during mental effort, therefore, is hardly comparable to the increases noted during any of these light muscular activities. The college professor engaged in severe mental effort at his desk in his library would in one hour increase his caloric output as a result of mental activity perhaps 3 or 4 calories. The housemaid sweeping and dusting the same room would, in approximately 3 minutes, have expended the same amount of excess calories.

Owing to the supposed close analogy between so-called "mental work" and muscular work and the well-known increased demand for energy during muscular work, a popular subject of frequent discussion has been the supposed special food requirements for mental workers. This discussion has favored two concepts, (1) that a nitrogen-rich diet such as that represented by fish is highly desirable, and (2) that because of the extreme fatigue, both mental and physical, following severe mental effort a heavy caloric diet is essential. After the ingestion of food, particularly protein, there is a well-known increase in the circulatory activity or the heart rate. That this may not, subjectively at least, result in a somewhat greater mental alertness is by no means proved

[1] Holmes, E. G., Annual Review of Biochemistry, Stanford Univ., 1932, 1, p. 487.
[2] Benedict, F. G., and A. Johnson, Proc. Amer. Philos. Soc., 1919, 58, p. 89.

or disproved by our experiments. On the other hand, it is an almost universal experience of intellectual workers that after a heavy meal mental activity is definitely inhibited. It seems needless to emphasize here (although our experiments do not contribute information on this point) that the long-retained conception of the importance of fish as a brain food is without basis. That lecithin or other phosphorus-rich substances in the brain may possibly participate in the mental activity is wholly speculative. The only experimental support for such speculation is the apparent increase in the phosphorus content of the plasma noted in the experiments of Kestner and Knipping.[1] Certainly there can be no thought of any correlation between the intake of phosphorus-rich material, such as fish, and mental efficiency.

The fact that mental effort results in an increase in the oxygen consumption and the heat production of only approximately 4 per cent means that (regardless of whether this increase is ascribable solely to mental activity or is more probably one of the concomitants of mental activity without any specific localization of the increase) the specific energy needs during severe mental effort would be met by a very small caloric increase in the diet. The caloric output of the average normal adult, post-absorptive and at rest, is approximately 60 or 70 calories per hour. An increase of 4 per cent in energy expenditure would represent at the most approximately 3 or 4 calories per hour. From the food standpoint the increase in metabolism during an hour of severe mental activity, that is, approximately 4 calories per hour, would be supplied by about 1 gram of cane sugar, 1 1/2 grams of white bread, 4 grams of banana (edible portion), or (in a more energy concentrated food) half of a peanut. These figures only serve to emphasize more sharply the extremely small increase in energy expenditure accompanying intense, sustained mental effort. It is our belief, furthermore, that this increase can in no wise be ascribed to a proportionate increase in the oxidative activity of the cells of the brain.

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[1] Kestner, O., and H. W. Knipping, Klin. Wochenschr., 1922, 1. Jahrg., No. 27, p. 1353.